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Calculating the average natural recharge in large areas as a factor of their lithology and precipitation

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Abstract

In an area as large as Spain, it is shown by statistical inference on a sample of 875 springs (with discharges greater than $10\,l\,s^{-1}$), whose average flow, lithology and catchment areas are known, and which were grouped into regions of contrasting rainfall, that the average annual recharge is a fixed fraction of annual rainfall for each lithology. Recharge rates have thus been established with respect to rainfall for six lithological groups of different permeability: sands, gravels and generally alluvial formations 8.3%; conglomerates, 5.6%; sandstones, 7.3%; limestone and dolomite 34.3%; marls, marly limestones, silts and clays, 3.3%; and hard rocks, 1.3%. Since Spain can be considered to be representative, given its large size and a highly varied lithology, topography and rainfall, these recharge rates with respect to rainfall are probably quasi-universal values, which can be used to estimate the average recharge or average groundwater resources of large regions in any part of the world (except in special cases such as areas that have permafrost). In any case, the recharge rates can be adapted for each region according to its particular characteristics. Rainfall and lithology data are abundant, and so the method can be widely used to calculate hydraulic balances. The method has been applied to the Duero basin in Spain and to other European countries (Portugal, Ireland and Italy), obtaining recharge results that are very similar to those calculated by other methods.

1 Introduction

The study of the natural recharge to aquifers is highly important since it is directly related to assessing groundwater resources and vulnerability of aquifers to pollution.

The factors that determine natural recharge are many, and include climate, geology and soil type (Kennet-Smith et al., 1994), land-use, hydrogeological characteristics and topography (Cherkauer and Ansari, 2005). When large regions are considered, some factors may diminish in importance while others increase. Over very large regions, there may be three fundamental factors: precipitation, temperature (which determines evaporation, evapotranspiration and to certain extent the vegetation type), and the lithology of the outcrops.

The lithology is largely responsible for determining the recharge rate with respect to the amount of precipitation. It is the decisive factor in determining the presence and magnitude of aquifers. Meanwhile, lithology and geology together tend largely to determine the nature and thickness of the dominant soil types in the regions. However, it is possible that other factors, such as topography, vegetation and land-use assume less importance, since over large regions, contrasting characteristics tend to compensate one another and cancel each other out, for example, mountains-plains and forests-cultivated areas.

Methods for calculating recharge are also numerous and varied and usually include uncertainties in the results obtained. This means that it is advisable to apply more than one method, if possible. In publications by Simmers (1988), Lerner (1997) and Scanlon et al. (2002), the different techniques for estimating recharge can be seen. The type of method and the spatial and time scales chosen depend on the purpose the calculation is to serve.

The method proposed here has as its goal the overall evaluation of groundwater resource of a country or large region, and this allows a wider range of both time and spatial scales. On the temporal scale, we refer to average annual values, while the spatial dimension may be specified as a more or less extensive territory, depending on the level of detail available for rainfall and lithological distribution. Working on this large scale, the conclusion is reached that the average annual recharge per unit area of a certain lithology is a constant fraction of the average annual rainfall in that area. This conclusion has been reached by analysing observations for peninsular Spain and, although the results appear quite reliable, it would be advisable to confirm them in other areas.

The method does not aim to produce a spatial or cartographic distribution of recharge as its end result, but rather it obtains an average value for a large region in particular.

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However, to calculate the latter requires the support of the spatial distribution of the outcrops and of precipitation, although these represent intermediate steps in the calculation. An understanding of the cartography was gained by referring to Dzhamalov and Zektser (1999) and WHYMAP (2008).

2 Method

2.1 Generalisation of the distribution of the spring supplies according to discharge

In previous work (Sanz, 1996, 2001), using a sample of 17 305 springs distributed throughout peninsular Spain, obtained the distribution functions for flow, according to springflow discharge for each of the nine lithological groups into which the springs were classified. They conform to a generic function of the type:

$$a_i(x) = k_i\, x^{-ni}$$

where $a_i(x)$ represents the contribution of the springs of flow x; and k_i and n_i are parameters characteristic to each lithological group. The contribution of all the springs to each lithological group can be calculated by integrating $a_i(x)$ as follows:

$$A_i = \int_{0.01}^{\max} k_i\, x^{-ni}\, dx = k_i \left| \frac{x^{1-n_i}}{1-n_i} \right|_{0.01}^{\max}$$

where the integration limits extend from $0.01\,\mathrm{l\,s^{-1}} = 36\,\mathrm{l\,h^{-1}}$ as the lowest flow for a discharge to be considered a spring, to the maximum flow registered in each lithology. Once this integration is performed, it is seen that the contribution of the four lithologies that may be considered as impermeable (quartzite, slates, plutonic rocks and others) jointly contribute only 5.5% of the total, and therefore the number of lithological groups was reduced to five, thereby simplifying the estimates of recharge to a sample of 875 springs, grouped into four areas of peninsular Spain with significantly varying rainfall (Fig. 1).

This aspect is applied later in this paper, but we will first demonstrate how these contributions can be identified from aquifers that discharge via springs with appreciable discharges of water. These contributions do not identify any diffuse discharges draining to seas, rivers or lakes. Table 1 shows the functions of contributions according to discharge and the annual value of these flows.

It may be assumed that, for a specific lithology, the function of contributions is always of type (Eq. 1), but it has different parameters depending on whether the lithology is located in one place or another with different recharge. Moreover, it would be interesting to analyse the variation of these parameters as a function of the variables that can affect that recharge.

In several cases, it has been shown that, for a certain lithology, there is an excellent degree of correlation between aquifer recharge and the two variables of rainfall and air temperature. However, if referring to annual periods, the importance of rainfall is stands out, since the average temperature (and in consequence, the evapotranspiration, to a certain extent) hardly varies within a specific region.

Here, it is assumed that the greater or lesser natural recharge of a certain lithology (exponent $-n$) and its effects are revealed in the value of the parameter k. In addition to confirming these hypotheses in this study, it would also be interesting to verify them for other regions, since the most important conclusion would be that these functions could be applied to other countries or territories. In addition, to calculate the contributions, it would be sufficient to know the six lithological groups of the area and its rainfall. Not only could it be applied to other territories, but even within the same country, the annual variation could be calculated as a function of the rainfall for each year.

Since Spain has a very varied climate, we have tried, without looking further afield, to analyse how springs behave in four areas of different rainfall.

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2.2 Samples, lithology and geographic areas

Let us consider some questions that focus the programming of this statistical inference:

– Since we are dealing with annual values and even annual averages, the assumed relationship between recharge and the rainfall and temperature values is reduced to rainfall alone. As explained above, the average annual temperature varies little and has only limited influence on the average annual recharge.

– The estimates of the functions of inflows according to discharges in each lithology were made in our previous studies, based on the number of springs with a discharge of more than $10\,\mathrm{l\,s^{-1}}$. Among the reasons chosen for this threshold was that knowledge of these "large" springs was good and the sample could be considered complete; even within this group of springs, it was necessary to select those where the lithology of their recharge area was known.

– In the "remainder" lithological group (containing the lithologies considered only scarcely permeable), there is only one small spring (between $11\,\mathrm{l\,s^{-1}}$ and $50\,\mathrm{l\,s^{-1}}$), whilst for the other five lithological groups, the composition of the samples by the number of springs is as follows:

Limestones, Dolomites	664 springs
Alluvial sediments, sands and gravels	105 springs
Conglomerates	43 springs
Sandstones	23 springs
Marls, silts and clays	40 springs
Total	*875 springs*

– Since for each lithology, the aim is analyse the possible relationship between the inflow and the rainfall, the territory that corresponds to peninsular Spain was divided into four areas of differing average rainfall. Then the spring samples were assigned to each area. It was considered wise not to set up more than four areas

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so as not to restrict excessively the number of springs in each lithology in each geographic area.

The following four geographic zones were established, each with significantly different mean annual rainfall:

Areas	Rainfall ($mm\,yr^{-1}$)
Area 1: North (Cantabria and Galicia)	1428
Area 2: Centre (Duero, Tajo, Ebro and Catalonian C. I.)	660
Area 3: South (Guadiana, Guadalquivir, South)	563
Area 4: Levante (Júcar and Segura)	467
Average Peninsular Spain	684

2.3 Methodology and results of the parameter to be measured

For each of the 875 springs in our sample, the following data were recorded: geographic area, discharge, lithology and surface lithology of the aquifer feeding the spring.

These data were first classified by geographic area, lithology, discharge and surface lithology, to obtain the number of springs in each group. The results, together with the calculation of their relative hydraulic contributions are shown in Table 2.

The results in Table 2 were then combined with the average rainfall in each geographic area to produce the data shown in Table 3. This table reflects the recharge by unit area ($l\,m^{-2}$) compared to the average rainfall of the geographic area expressed in the same units. Thus, the percentage rainfall that has infiltrated is obtained for each lithology and geographic area.

The results obtained are highly significant since, the quotient derived for each lithological group shows hardly any differences between the various geographic areas. Infiltration of rainwater into the ground depends on, among other factors, the duration of the rainfall event, the moisture level of the soil, as expressed in Horton's law (1937). However, at a cumulative annual level, the percentage of natural recharge for a particular lithology is constant and is not influenced by the rainfall volume. The conclusion is reached that, provided the area considered is very large, the average annual recharge per surface unit of a certain lithology is a constant fraction of the average annual rainfall over this area.

Table 4 summarises the results in Table 3, together with the average, variance, standard deviation and relative error (%). These relative values range between 23.5% for conglomerates and 5.1% for sandstones and they can be indicative of the margin of error that can be accepted when making estimates using this method of recharge calculation.

The average value for the five lithologies considered together, weighting each type by the volume of recharge, is 10.8%. This value is close to that calculated for limestone, which is explained since most recharge occurs in this lithology.

These are indicative values as far as the error of these estimations is concerned, as other factors have to borne in mind, such as, e.g., the more reduced divisions for recording the rainfall variations instead of using average for a very large territory.

To be able to calculate the total recharge to peninsular Spain, there is a need to estimate the percent rainfall (P_i) that goes to recharge the group of scarcely permeable outcrops, denominated "other lithologies". Considering the small recharge to the lithologies in this group, we can calculate an average recharge based on the data in Table 1 for this group: area 168 963 km^2; recharge, 963.2 h m^3. Hence, the contribution per unit area is (963.2/168 963).100 = 0.000057 $km^3\,h^{-1}\,m^{-1}$ = 5.7 mm m^{-2}. However, as the average rainfall is 687 mm m^{-2}, the hydraulic contribution estimated before represents 0.83% of the rainfall.

2.4 Applying the calculation to peninsular Spain

The parameters used to establish the fraction of rainfall that is recharged form the basis of this calculation. In the absence of more accurate data, the annual national rainfall figure, i.e., 687 l m^{-2}, is taken for all the lithological groups. Accordingly, the data shown in Table 5 is produced.

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To calculate the contribution of the lithology, i, (in h m^3), the following formula has been used:

$$A(i) = S_i \times \text{precipitation} \times P_i \times 10^{-5}$$

where S_i is expressed in km^2, $A(i)$ in h m^3, and rainfall in l m^{-2}.

The results are quite similar to those in Table 1, which were obtained using the functions $a(x)$ of the contribution into each lithological type. In the overall calculation, the difference is less than 0.1%. The greatest difference occurs in the "conglomerates" group, currently calculated to be 5.5% greater than that shown in Table 1.

2.5 Adjustment of the results to represent the total natural recharge for Spain

For any lithological type, it has already been highlighted that the mean annual recharge is a fixed fraction of the mean annual precipitation that falls over this lithology, independent of its value.

Up to this point in the study, this fixed fraction has been determined by calculating the flow in the emerging springs, which together equate to some 17 326 $\text{hm}^3\,\text{yr}^{-1}$ for peninsular Spain. It has already been noted that the recharge on which previous calculations were based are summarised in Table 1, and that these were calculated from the mean annual flow of all springs, excluding diffuse flows to rivers, lakes and to the sea.

The mean annual recharge, expressed as a fraction of the groundwater component of river flow (from springs and diffuse discharges) and outflows to the sea, has been estimated for Spain as a whole for the period 1940/1940 to 1995/1996, as 28 719 $\text{h m}^3\,\text{yr}^{-1}$ (MIMAM, 2000). This value is somewhat higher than the one calculated in the present article (17 326 $\text{h m}^3\,\text{yr}^{-1}$). This leads to the supposition that the difference between these two figures (11 393 $\text{h m}^3\,\text{yr}^{-1}$) corresponds to the diffuse discharges to rivers, lakes and to the sea.

Given that infiltration into each lithology is a fixed fraction of the annual rainfall, and assuming that the differences are maintained, new values of P_i are obtained by

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multiplying the earlier figure of total natural recharge by 1.66, i.e., the ratio between the total natural recharge and spring discharge. Table 6 shows the factors P_i (percentage of rainfall converted to recharge in a lithology, i, in an annual water balance) obtained on this basis, for peninsular Spain.

The recharge under a natural regime for a particular territory or country can be calculated using the formula:

$$\text{Natural Recharge}\left(\text{h m}^3\right) = S_i \times P_m \times P_i \times 10^{-5}$$

where S_i expresses the surface of the lithology, i, in km^2 and P_m, the average annual rainfall in l m^{-2}.

The calculations highlight the limestone and dolomite lithologies. These occupy 15% of the total area, yet provide 61.4% of the total natural recharge to peninsular Spain. In contrast, the group of scarcely permeable rocks, which occupy 39% (more than a third of the territory), only provide 5.3% of the total recharge.

The factors, P_i in Table 6 refer to peninsular Spain. Strictly speaking, their ideal application would be in subregions of Spain itself, as in the case of the Duero catchment described in Sect. 3.1

It is clear that for small or medium-sized regions, the ratio of recharge destined for springflow/total recharge, can be highly variable. However, for large regions, thousands of km^2 in extent, the ratio could resemble that estimated for Spain as a whole.

Spain is considered to be sufficiently large and representative, encompassing a wide variety of geology, lithology, rainfall, relief and vegetation. In addition, the total recharge is known with reasonable precision.

The proportion of recharge destined to springflow/total recharge (calculated using methods different to those used in our study) yields results for Portugal (1.58), Ireland (1.54), Italy (1.81) and the Duero catchment (1.5), which are values close to that obtained for peninsular Spain (1.66).

These values are shown in Table 8, which shows just the calculated recharge destined to springflow. It allows the P_i for Spain to be used with certain guarantee.

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In any case, the proportionality would have to be adjusted to the total recharge in those regions where there are previous reliable calculations. Thus, rates of total recharge could be obtained for each region based on their different precipitation (P_i).

During the period 1940–1990, the procedure followed in Spain to determine total natural recharge was the distributed modelling of the basic components of the hydrological cycle on a countrywide scale (Estrela et al., 1999).This model makes use of the information recorded at gauging stations, weather data, and the characteristics of the aquifer examined. This conceptual, distributed hydrogeological model (which takes the spatial variability of all the hydrological data into account) can simulate the mean monthly flows (natural regime) at any point in the country's hydrographic network by reproducing the essential processes of water transport in the different phases of the hydrological cycle. In each of the approximately 500 000 cells of dimensions 1000 × 1000 m into which Spain can be divided, it contemplates the principle of continuity and establishes the laws of transfer and sharing between the different storage zones on monthly scale.

The model inputs used in the parent work were monthly rainfall and temperature data. Times of historic flow were taken as simulation or calibration points. Also taken into account were the maximum moisture storage capacity of the soil, the maximum infiltration capacity, and the recession coefficients of the aquifers.

3 Examples of application

3.1 Application to calculating the natural recharge in the Duero basin (Spain)

The Duero basin lies in northwest Spain and covers an area of almost 90 000 km^2. It receives an average rainfall of 621.3 mm yr^{-1}. It is a large sedimentary basin containing detrital and marly deposits, surrounded by predominantly carbonate mountain chains (Fig. 2).

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The basin was divided into 11 areas corresponding to, or delimited by, isohyets in 100 m increments, from 350 $l\,m^{-2}$ to 1450 $l\,m^{-2}$; with which the class marks of each area or interval a rounded with rainfall of 400 $l\,m^{-2}$, 500 $l\,m^{-2}$ etc. Areas occupied by each of the lithological groups were calculated for each of these 11 areas.

These data were calculated using the 1:400 000 lithological map, marking the area of each lithological group and the average rainfall on each 5 × 5 km grid square. Π was then used from the table. The results for the entire Duero basin give the distribution shown in Table 7.

By this means, a total contribution of 3311.5 $h\,m^3\,yr^{-1}$ was obtained, which is very similar to that obtained by Estrela et al. (1999) using a distributed mathematical model that applied to the whole of Spain and which gave an annual average natural recharge value of 3000 $h\,m^3\,yr^{-1}$ for the Duero basin.

3.2 Application to calculating the natural recharge in several European countries

As a means of illustration, the method has been applied to four western European countries: Spain, Portugal, Ireland and Italy, which have a sufficiently large area, varied lithology and varied rainfall. In addition, Spain is the most arid country in Europe and Ireland the wettest (Fig. 3). It is also assumed that the natural recharge has been evaluated sufficiently accurately. Table 10 summarises the area, average rainfall period 1901/1902–1995/1996 (CRU, 1998), and the average recharge calculated in previous work, along with the recharge calculated in the current study.

For Portugal, the recharge calculations were based on the separation of the base flow of certain rivers. Using the mean recharge values obtained for a number of catchments, regression lines were fitted with mean precipitation, which were then extrapolated to the remaining catchments (Lobo Ferreira et al., 1995; Oliveira et al., 1997; Carmona, 1999).

For Ireland, water balances were calculated from the real evapotranspiration using the Penman formula. Where possible, the recharge figure thus computed was compared with a recharge estimate derived from base-flow separations from river hydrographs.

In Italy, catchment water balance studies are performed where many data exist, based on the evaluation of the basin output (base river flow, direct flow to the sea, abstractions); analogy or mathematical models can also be used: infiltration values are then extrapolated to other formations.

For Spain, the 1:400 000 map of Oriol Riba (1969) was used for lithological data, while for Portugal, Ireland and Italy, the CEC-Eurostat GISCO/1995 maps were used, which group the numerous differentiated lithologies into the six groups being considered. The lithological distribution can be seen in Table 8 and Fig. 4. To calculate the recharge, the coefficients P_i from Table 6 and the average rainfall for each country were used.

The lack of precision resulting from the use of average rainfall will incur an error, though this is partially cancelled out by the fact that very extensive areas are being considered. The results obtained (Table 9), however, can be considered as quite acceptable, except, perhaps for Italy. In the case of Italy, the average recharge figure can probably be explained by two reasons: the first is that limestone outcrops in Italy are located mainly in areas receiving the highest rainfall, so that the higher than average rainfall should have been used in the calculations; secondly, Italy has a considerable area of volcanic rocks, whose recharge rate with respect to rainfall is unknown, although it is supposed that it is quite high.

4 Conclusions

This study presents a new technique for estimating the average natural recharge of large regions based on establishing indices or rates of recharge as a function of rainfall for six lithological groups of varying permeability.

The method was initially proven using a statistically large sample of springs, which was used to establish specific distribution functions of water supply of springs

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according to their discharge for different lithological groups in peninsular Spain (Sanz, 2001). This exercise confirms the validity of the general normal logarithmic function devised by Sanz (1996).

Subsequently, statistical inferences were made on the complete sample of springs with discharges exceeding $10\,\mathrm{l\,s^{-1}}$. The discharge and lithology of their recharge areas were known so that the springs could be grouped into four regions within Spain with varying rainfall. In this way, we showed that recharge is a fixed fraction of the average rainfall for each lithology and that it is independent of the temperature. Intermediate calculation steps were performed to validate the method, applying it to the Duero basin and to peninsular Spain.

The recharge rates, depending on rainfall, were obtained by adjusting provisional recharge rates obtained to the total estimated recharge under a natural regime in Spain complied by the L. B. A. (MIMAM, 2000) so that diffuse discharge were also considered.

The following recharge rates with respect to rainfall to Spain were established for the six lithological groups considered.

Lithology	The recharge rate of precipitation to groundwater to Spain (%)
Alluvial sediments, sands, gravels	8.3
Conglomerates	5.6
Sandstones	7.3
Limestones, Dolomites	34.3
Marls, limey marls, gypsum, silts, clays	3.3
Hard Rocks	1.3

The method proposed is already adjusted, and therefore needs no historical series. Calculation of the average recharge is based on knowledge of the surface distribution of a river basin, region or country, according to the six lithological groups. Once this distribution is known, the calculation can be applied to the average or annual recharge with prior knowledge only of the annual rain falling over each lithological group. These are applied to the recharge rates of Spain, which can be considered

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representative, or from other recharge rates that have been adjusted to each region. Thus, the method may be applied, except in very cold regions or other extreme cases (such as permafrost) to any region or country, since the rainfall and lithology data are easily acquired.

The method has been applied to the overall evaluation of the groundwater resources of the Duero basin in Spain and to four European countries, comparing the results with official statistics (Eurostat, 1998) obtained using different methods.

Our method allows the groundwater resources throughout the world to be evaluated approximately through the knowledge of readily available data: lithology and average rainfall.

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Table 1. Hydraulic contribution distribution functions and annual hydraulic contribution.

Lithologic groups	Area [km^2]	$a(x)$ function of hydraulic contributions[1]	Literal interpretation of part[2] of $a(x)$ [h m^3]	Annual hydraulic contribution h m^3	%
Alluvials, sands, gravels	80 104	$252.0 \times^{-1.08}$	$\int^{-1.08} x dx = 11.0$	2772.0	16.0
Conglomerates	31 141	$55.4 \times^{-0.89}$	$\int^{-0.89} x dx = 12.5$	688.8	4.0
Sandstones	19 213	$64.5 \times^{-1.02}$	$\int^{-1.02} x dx = 9.2$	593.4	3.4
Limestones and dolomites	74 582	$146.3 \times^{-1.27}$	$\int^{-1.27} x dx = 11.9$	1741.0	10.1
Marls, silts, clays	123 963	$96.8 \times^{-1.44}$	$\int^{-1.44} x dx = 10.0$	963.2	5.5
All groups	497 477	$1069 \times^{-0.91}$	$\int^{-0.91} x dx = 16.2$	17312.1	100.0

[1] $a(x)$ in h m^3 and x in l s^{-1},
[2] Integrals have as lower limit 0.01 l s^{-1} and as higher the maximum of each group.

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Table 2. Number of springs according to flow, contributions and lithological areas.

Flow intervals ($l\,s^{-1}$)	Class Marks	Number of springs – Geographic zones 1	2	3	4	Total	Hydraulic Contributions in $h\,m^3\,yr^{-1}$ – Geographic zones 1	2	3	4	Total
Lithology 1. Alluvials, sands and gravels											
11–50	30	5	17	39	16	77	4.7*	16.1	36.9	15.1	72.8
51–100	75	1	3	8	7	19	2.4	7.1	18.9	16.5	44.9
101–200	150	–	–	4	2	6	–	–	18.9	9.5	28.4
201–500	350	–	–	1	–	1	–	–	11.0	–	11
501–1000	750	–	–	1	–	1	–	–	23.7	–	23.7
1001–1500	1250	–	–	–	–	–	–	–	–	–	–
1501–2000	1750	–	1	–	–	1	–	55.2	–	–	55.2
2001 and more	2000	–	–	–	–	–	–	–	–	–	–
All		6	21	53	25	105	7.1	78.4	109.4	41.1	236
Lithological area (km^2)							100	2579	3666	1760	8105
Lithology 2. Conglomerates											
11–50	30	1	8	10	8	27	1	7.5	9.5	7.6	25.6
51–100	75	–	4	2	2	8	–	9.5	4.7	4.7	18.9
101–200	150	1	2	2	1	6	4.7	9.5	9.5	4.7	28.4
201–500	350	1	–	1	–	2	11	–	11.1	–	22.1
All		3	14	15	11	43	16.7	26.5	34.8	17	95
Lithological area (km^2)							330	1178	1904	1110	4522
Lithology 3. Sandstones											
11–50	30	6	1	11	3	21	5.9	1	10.8	2.9	20.6
51–100	75	–	1	–	1	2	–	2.4	–	2.4	4.8
All		6	2	11	4	23	5.9	3.4	10.8	5.3	25.4
Lithological area (km^2)							87	125	427	267	906

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Table 2. Continued.

Flow intervals ($l\,s^{-1}$)	Class Marks	Number of springs					Hydraulic Contributions in $h\,m^3\,yr^{-1}$				
		Geographic zones					Geographic zones				
		1	2	3	4	Total	1	2	3	4	Total
Lithology 4. Limestones and Dolomites											
11–50	30	62	181	121	92	456	58.7	171.2	114.5	87.0	431.4
51–100	75	5	28	29	15	77	11.8	66.2	68.6	35.5	182.1
101–200	150	6	12	17	12	47	28.4	56.8	80.4	56.8	222.4
201–500	350	2	12	12	11	37	22.1	132.5	132.5	121.4	408.5
501–1000	750	2	14	5	9	30	47.3	331.1	118.3	212.9	709.6
1001–1500	1250	2	2	–	5	9	78.8	78.8	–	193.1	354.7
1501–2000	1750	–	1	1	2	4	–	–	55.2	110.4	220.8
2001 and more	2000	1	1	1	1	4	63.1	63.1	63.1	63.1	252.3
All		80	251	186	147	664	310.2	954.8	632.6	884.2	2781.8
Lithological area (km^2)							1189	6988	5126	9146	22 449
Lithology 5. Marls, limely marls, silts and clays											
11–50	30	6	7	16	4	33	5.7	6.6	15.1	3.8	31.2
51–100	75	1	–	2	–	3	2.4	–	4.7	–	7.1
101–200	150	–	1	3	–	4	–	4.7	142.0	–	18.8
All		7	8	21	4	40	8.1	11.3	34.0	3.8	57.2
Lithological area (km^2)							260	831	3113	373	4577

*30.5 $(3600 \times 24 \times 365)/10^9 = 30.5 \times 0.031536 = 4.7304$

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Table 3. Percentage of precipitation recharged in each lithological group.

Geographics zones	Area S (km^2)	Hydraulic Contribution A (km^2)	A/S ($l\,m^{-2}$)	Precipitation P ($l\,m^{-2}$)	% Precipitation infiltrated P_i
Lithology 1. Alluvials, sands y gravels					
North	100	7.1	71.1	1428	5.0
Center	2579	78.4	30.4	660	4.6
South	3606	109.4	29.8	563	5.3
Levante	1760	41.1	23.4	467	5.0
All	8105	236	29.1	583*	5.0
Lithology 2. Conglomerates					
North	330	16.7	50.6	1428	3.5
Center	1178	26.5	22.5	660	3.4
South	1904	34.8	18.3	563	3.2
Levante	1110	17	15.3	467	3.3
All	4522	95	21	627*	3.4
Lithology 3. Sandstones					
North	87	5.9	67.8	1428	4.7
Center	125	3.4	27.2	660	4.1
South	427	10.8	25.3	563	4.5
Levante	267	5.3	19.9	467	4.3
All	906	25.4	28	631*	4.4

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Table 3. Continued.

Geographics zones	Area S (km^2)	Hydraulic Contribution A (km^2)	A/S (l m^{-2})	Precipitation P (l m^{-2})	% Precipitation infiltrated P_i
Lithology 4. Limestones and Dolomites					
North	1189	310.2	260.9	1428	18.3
Center	6938	954.8	136.6	660	20.7
South	5126	632.6	123.4	563	21.9
Levante	9146	884.2	96.7	467	20.7
All	22 449	2781.8	123.9	600*	20.7
Lithology 5. Marls, limely marls, silts and clays					
North	260	8.1	31.2	1428	2.2
Center	831	11.3	13.6	660	2.1
South	3113	34	10.9	563	1.9
Levante	373	3.8	10.2	467	2.2
All	4577	57.2	12.5	622*	2

*Weight mean values by surface.

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Table 4. Percentage of precipitation destined to recharge (P_i).

Geographics zones	1. Alluvials, sands and gravels	2. Conglomerates	3. Sandstones	4. Limestones and Dolomites	5. Marls, Silts and Clays
North	5.0	3.5	4.7	18.3	2.2
Center	4.6	3.4	4.1	20.7	2.1
South	5.3	3.2	4.5	21.9	1.9
Levante	5.0	3.3	4.3	20.7	2.2
Mean ($\bar{X}$)	5.0	3.4	4.4	20.7	2.0
σ^2	0.17	0.67	0.05	5.4	0.1
σ	0.4	0.8	0.2	2.3	0.3
$\sigma/\bar{x}$ (%)	8.2	23.5	5.1	11.2	15.1

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Table 5. Estimate of recharge in peninsular Spain.

Lithological Groups	Area S_i (10^3 km^2)	Precipitation (l m^{-2})	P_i (%)	Hydraulic Contribution (h m^3)	Showed in the Table 1
Alluvials, sands and gravels	80.104	687	5.0	2752	2752
Conglomerates	31.141	687	3.4	727	689
Sandstones	19.213	687	4.4	581	593
Limestones and Dolomites	74.582	687	20.7	10 606	10 554
Marls, silts, clays	123.464	687	2.0	1696	1741
Others	168.973	687	0.8	964	963
All	497.477			17 326	17 312

Table 6. Recharge rates with respect to precipitation, according to lithological group.

Lithologies	P_i (%)	Recharge of peninsular Spain km^2	%
Alluvials, sands, gravels	8.29	4562	15.9
Conglomerates	5.63	1204	4.2
Sandstones	7.29	962	3.4
Limestones, Dolomites	34.31	17 580	61.4
Marls, silts, clays	3.32	2816	9.8
Others	1.32	1532	5.3
Total		28 656	100

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Table 7. Calculation of hydraulic contributions to the Duero catchment (Spain).

Precipitation ($l\,m^{-2}$)		Lithological Areas (km^2)						
Intervals	Class marks	Alluvials	Conglomerates	Sandstones	Limestones	Marls	Others	Total
350–449	400	6311	1126	80	1122	7327	852	16 818
450–549	500	5296	1803	193	3580	7184	3500	21 556
550–649	600	2403	2209	237	1387	2992	3169	12 397
650–749	700	1020	1431	223	893	1072	3336	7975
750–849	800	793	523	190	164	269	6352	8291
850–949	900	1035	1047	165	329	1094	1857	5527
950–1049	1000	141	262	152	180	513	2858	4106
1050–1149	1100	–	–	19	106	–	980	1105
1150–1249	1200	–	–	–	–	–	–	–
1250–1349	1300	–	–	16	56	–	481	553
1350–1449	1400	10	–	–	88	–	534	632
All		17 009	8401	1275	7905	20 451	23 919	78 960
%		21.5	10.6	1.6	10	25.9	30.4	100
Spain %		16.1	6.3	3.9	15	24.8	33.9	100
Precipitation		532.02	631.08	722.35	583.93	527.17	768.81	621.3
Hydraulic contribution ($h\,m^3$)		751	296.9	67.2	1583.2	355.8	2574	3311.5

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Table 8. Calculation of the average recharge for springs, for four European countries (Spain, Portugal, Ireland and Italy) and the classification of lithologies from CEC-Eurostat GISCO (1995) into six groups.

Country	Lithology	Area (km^2)	P_m ($l\,m^2$)	P_i	Recharge for spring ($hm^3\,yr^{-1}$)
Peninsular Spain	Alluvials	80 104	687	0.05	2751.6
	Conglomerates	31 141	687	0.034	727.4
	Sandstones	19 213	687	0.044	580.8
	Limestones	74582	687	0.21	10 760.0
	Marls	123 464	687	0.02	1696.4
	Others	168 973	687	0.008	928.6
	Total	497 477	687	–	17 444.8
Portugal	Alluvials	12 485	882	0.05	550.6
	Conglomerates	0	882	0.034	0
	Sandstones	13 516	882	0.044	524.5
	Limestones	5500	882	0.21	1018.7
	Marls	1678	882	0.02	29.6
	Others	56 720	882	0.008	400.2
	Total	89 898	882	–	2523.6
Ireland	Alluvials	3384	1150	0.05	194.6
	Conglomerates	0	1150	0.034	0
	Sandstones	11 758	1150	0.044	595.0
	Limestones	24 446	1150	0.21	5903.7
	Marls	0	1150	0.02	0
	Others	29 989	1150	0.008	275.9
	Total	69 577	1150	–	6969.2
Italy	Alluvials	80 722	982	0.05	3963.4
	Conglomerates	0	982	0.034	0
	Sandstones	31 812	982	0.044	1374.5
	Limestones	71 911	982	0.21	14 829.5
	Marls	59 212	982	0.02	1162.9
	Others	41 204	982	0.008	323.7
	volcanics	17 694	982	0.12	2085
	Total	302 557	982	–	23 739

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Table 8. Continued.

Country	Recharge for springs estimated in this work ($hm^3 yr^{-1}$)	Total Recharge ($hm^3 yr^{-1}$)	Recharge for spring/Total Recharge
Peninsular Spain	17 444.8	28 908[1]	1.66
Portugal	2523.6	4000[2]	1.58
Ireland	6969.2	10 800[3]	1.54
Italy	23 739	43 000[4]	1.81
Duero Basin	2005.2	3000[1]	1.5

[1]MIMAM (2002); Estrela et al. (1999).
[2]MIMAM (2002b); Carmona (1999).
[3]MIMAM (2004); EEA (2001); WRI (2001).
[4]MIMAM (2002b); IRSA (1997).

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Table 8. Continued.

No	Lithological Groups	Lithology of Eurostat-GISCO (Code, description)
1	Alluvials, sands and gravels	100, Undifferenciate alluvial deposits (or glacial deposits); 110, River alluvium; 111, Old fluviatile deposit (tertiary); 112, Terraces; 130, Glaciofluvial deposits; 131, Till; 140, Glaciofluvial drift; 400, Sandy materials; 410, Old sandy sedimentary deposits; 411, secondary sands; 412, Tertiary sands; 420, Alluvial or glaciofluvial sands; 421, Glacial sands; 422, Sandy gravely materials; 430, Eolian sands; 431, Locally coversand; 440, Coastal sands (Dune sands); 441, Shelly coastal sands; 442, Non calcareous coastal sands; 600, detrital formations
2	Conglomerates	620, Breche + Poudingues
3	Sandstones	450, Sandstone; 451, Calcareous sandstone (Macigno); 452, Ferrugineous sandstone (old red sandstone); 453, Clayey sandstone; 454, Soft quartz sandstone; 455, Hard quartz sandstone; 610, Arkose; 630, Flysch + Molasse
4	Limestones and Dolomites	200, calcareous rocks; 210, Limestone; 211, Primary limestone (carboniferous); 212, Secondary limestone; 213, Tertiary limestone; 214, ferrugineous limestone; 215, Hard limestone; 216, Soft limestone; 220, secondary chalk; 250, Dolomite

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Table 8. Continued.

No	Lithological Groups	Lithology of Eurostat-GISCO (Code, description)
5	Marls, Silts and Clays	120, Estuarine/Marine alluvium; 230, Marl; 231, secondary marl; 232, Tertiary marl; 233, Gypseous Marl; 300, Clayey materials; 310, Old clayey sedimentary deposits; 311, Primary clay and sandstone; 312, secondary clay; 313, Tertiary clay; 320, Alluvial or glaciofluvial clay; 321, Tertiary alluvial clay; 322, Glacial clay (tertiary and quaternary); 323, Gravely clay; 324, Boulder clay; 330, Residual clay from calcareous rocks; 331, flint clay (argile a silex); 332, Siderolith formations; 340, Claystone mudstone; 500, Loamy materials; 510, Residual loam; 511, Old loam (Touyas); 512, Stony loam; 513, Clay loam; 520, Eoliam loam; 521, Loess; 522, Locally loess; 523, Sandy loess; 530, Siltstone; 640, Ranas
6	Others	456, Quartzite; 700, Crystalline rocks; 710, Acid crystalline rocks (+ migmatites); 711, Granite; 712, Diorite, Quartzodiorite; 720, Nod acid crystalline rocks (+ migmatites); 721, Syenite; 722, Gabbro; 730, Crystalline metamorphic rocks; 731, Gneiss; 740, Schists; 741, Micaschists; 742, Slates; 743, Shales; 744, Calcschists; 745, Green schists; 750, Other metamorphic rocks; 800, Volcanic rocks; 810, Acid volcanic rocks; 820, Basic volcanic rocks; 821, Phonolites; 822, Basalt; 900, Other rocks

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Table 9. Calculation of mean recharge in four countries in Europe (Spain, Portugal, Ireland and Italy).

Country	Lithology	Area (km^2)	P_m ($l\,m^{-2}$)	P_i	Recharge ($hm^3\,yr^{-1}$)
Peninsular Spain	Alluvials	80 104	687	0.083	4567.6
	Conglomerates	31 141	687	0.056	1198.1
	Sandstones	19 213	687	0.073	963.6
	Limestones	74 582	687	0.343	17 574.6
	Marls	123 464	687	0.033	2799.1
	Others	168 973	687	0.014	1625.2
	Total	497 477	687	–	28 728.2
Portugal	Alluvials	12 485	882	0.083	913.9
	Conglomerates	0	882	0.056	0
	Sandstones	13 516	882	0.073	870.24
	Limestones	5500	882	0.343	1663.8
	Marls	1678	882	0.033	48.83
	Others	56 720	882	0.014	700.37
	Total	89 898	882	–	4197.14
Ireland	Alluvials	3384	1150	0.083	323
	Conglomerates	0	1150	0.056	0
	Sandstones	11 758	1150	0.073	987.1
	Limestones	24 446	1150	0.343	9642.7
	Marls	0	1150	0.033	0
	Others	29 989	1150	0.014	482.8
	Total	69 577	1150	–	11 435.6
Italy	Alluvials	80 722	982	0.083	6579.3
	Conglomerates	0	982	0.056	0
	Sandstones	31 812	982	0.073	2280.4
	Limestones	71 911	982	0.343	24 421.5
	Marls	59 212	982	0.033	1918.8
	Others	41 204	982	0.014	566.48
	volcanics	17 694	982	0.2*	3539
	Total	302 557	982	–	39 305.5

* Estimative

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Table 10. Comparison of estimated mean recharge in earlier published works, and in the present study, for Spain, Portugal, Ireland and Italy.

Country	Area (km^2)	Mean Precipitation* in $mm\,yr^{-1}$	Mean Recharge ($hm^3\,yr^{-1}$) Previous works	Estimations of this work
Spain (peninsular)	497 477	687	28 908[1]	28 728.2
Portugal	89 898	882	4000[2]	4197.14
Ireland	69 577	1150	10 800[3]	11 435.6
Italy	302 557	982	43 000[4]	39 305.5

*period 1940/1941–1995/1996

Source: [1]MIMAM (2000); Estrela et al. (1999). [2]MIMAM (2000b); Carmona (1999). [3]MIMAM (2004); EEA (2001); WRI (2001). [4]MIMAM (2000b); IRSA (1997).

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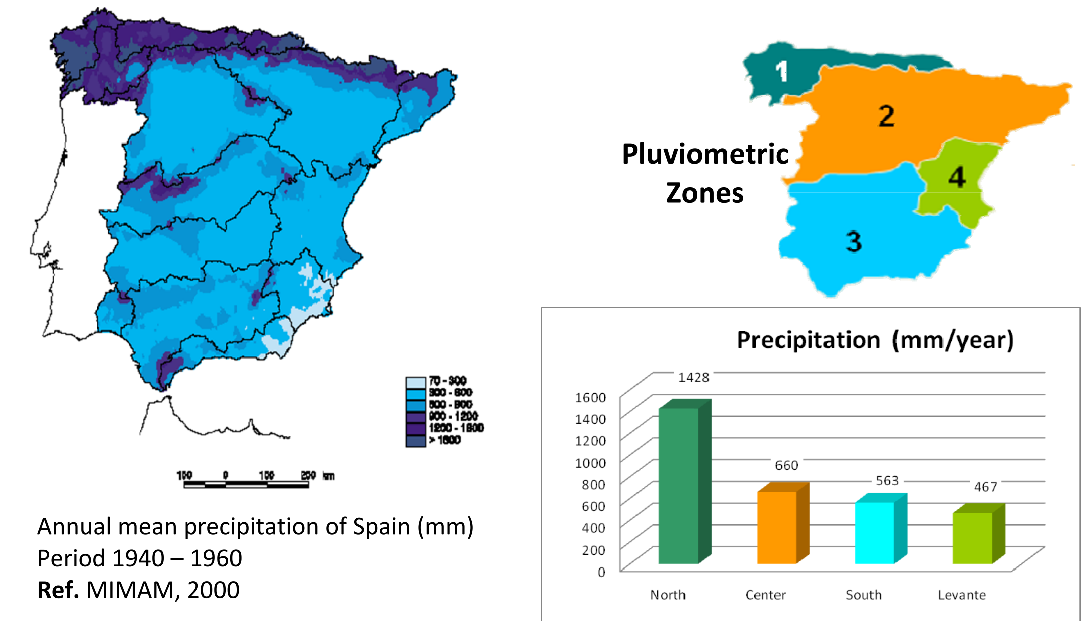

Fig. 1. Pluviometric Zones and Mean precipitation values of Spain.

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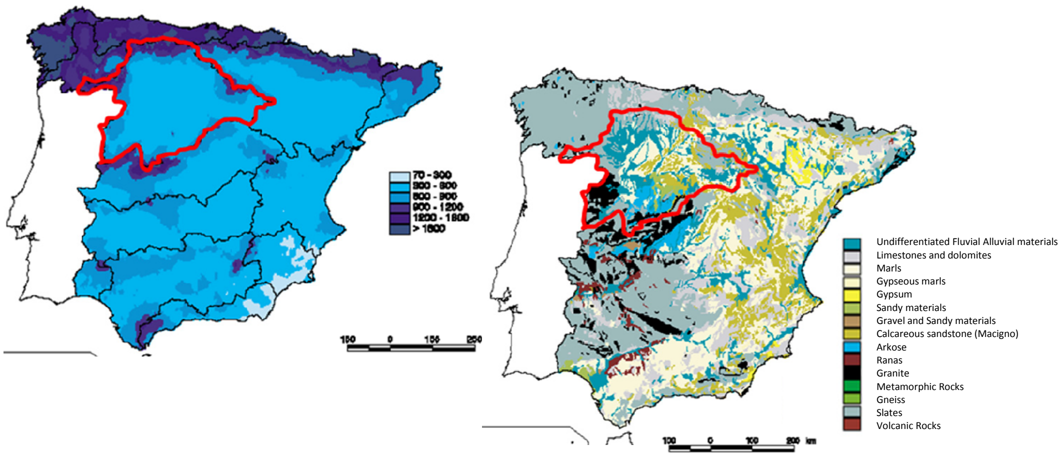

Fig. 2. Lithology Map and precipitation of Duero Basin (Spain). Maps extracted of: MIMAM, 2000 (Spain). Libro Blanco del Agua.

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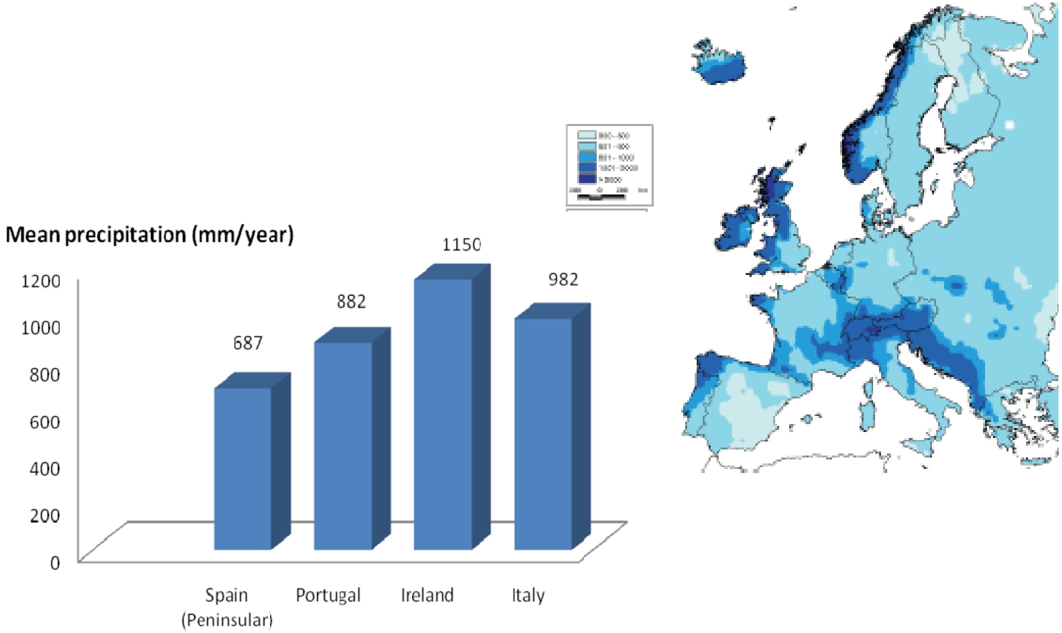

Fig. 3. Annual Mean Precipitation in Europe (mm); period 19940/1941–1995/1996. Source of Map: Extracted of MIMAM, 2004. Aguas Continentales en la Unión Europea (CEDEX).

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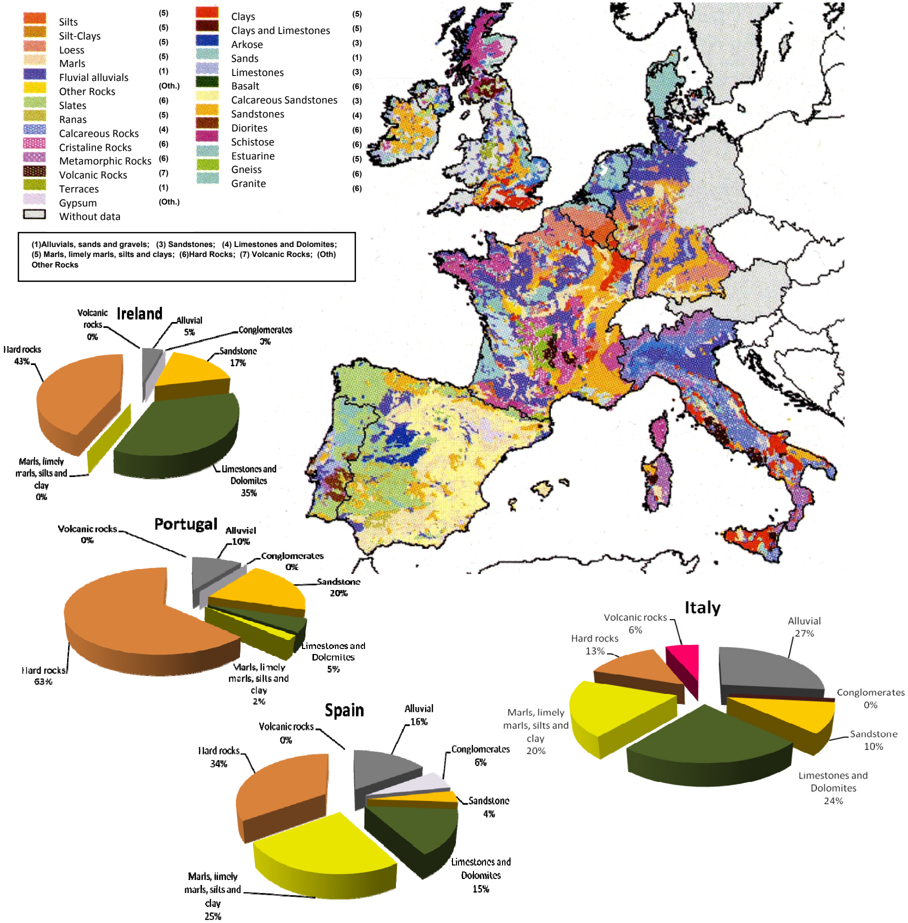

Fig. 4. Lithology Map of Europe and Lithological groups for some European countries. Map extracted of: MIMAM, 2004. Las aguas continentales en la Unión Europea (CEDEX).

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