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A Method for the Assessment of Underground Renewable Reserves for Large Regions: Its Importance in Water Supply Regulation

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Abstract: The growing interest in groundwater as a sustainable resource for water supply regulation is noteworthy. Just as surface reservoirs in many countries are primarily designed to manage seasonal fluctuations throughout the year, aquifers possess significant reserves, making them particularly well suited for interannual regulation, especially during droughts. In the face of climate change, this form of regulation may increasingly highlight the importance of groundwater resources. For instance, the temporary use of groundwater reserves through intensive pumping in arid or semiarid regions, compensating for seasonal or interannual variations in natural water recharge, can significantly affect aquifers. The exploitation of groundwater reserves may lead to adverse effects over time, eventually being deemed overexploitation and subject to environmental or even legal issues. This work assesses the interannual regulation capacity of aquifers and estimates the groundwater renewal rates and periods for aquifers according to river basins. We first present the mathematical background and development of a method to assess the hydrodynamic volumes (renewable groundwater reserves) in large regions. This method builds on prior knowledge of the distribution functions of spring water contributions based on their discharge and for lithological groups exhibiting similar hydrogeological behavior. Furthermore, it establishes a relationship between spring discharges and hydrodynamic volumes, facilitating the integration of the latter based on discharge. Although proposed for Spain, the method can also be implemented to other regions where data are available.

Keywords: groundwater reserves; hydrodynamic reserves assessment; groundwater and water supply; interannual regulation; aquifer sustainability

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1. Introduction

The intermittent or non-continuous use of groundwater reserves is becoming decisive in arid regions that frequently experience droughts, such as those with a Mediterranean climate (e.g., Spain and neighboring countries affected by the severe 2022 drought). Intensive pumping of aquifers can offset seasonal or inter-annual variations in natural water recharge, thus ensuring a reliable water supply for various needs [1]. This practice serves as an assurance against water scarcity. However, while the strategic exploitation of groundwater reserves aids in regulating water resources, it may also be classified as groundwater over-exploitation, subject to environmental and legal constraints [1].

According to the International Association of Hydrogeologists [2], climate change in the Mediterranean fringe will mean greater inter-annual variability in rainfall and therefore in natural recharge, more frequent and prolonged droughts, and the need for greater use of reserves through strategically located "drought wells". In other words, an effective integrated management of surface and groundwater resources requires a more strategic use of groundwater during drought periods through increased temporary extraction from regular sources, as well as through "drought wells" specifically designed and reserved to address such situations.

Knowledge of groundwater reserves is also important because they constitute the natural hydrodynamic store that feeds the base and ecological flow of rivers. Their discharge according to their recession depletion informs us of the regulating power of the aquifers through the rivers and springs that drain them, as well as the vulnerability of the aquifers to droughts, for example.

Groundwater reserves encompass the total quantity of drainable water within an aquifer or aquifer system, calculated by multiplying the aquifer's volume by its specific yield. Due to the complexity of acquiring this data at the scale of large basins or entire countries, calculations are typically restricted to specific, intensively exploited aquifers of significant interest. In such cases, the extracted volumes and declines in piezometric levels are systematically monitored over time. Part of the so-called hydrodynamic or renewable reserves can generally be estimated by analyzing depletion recessions in spring hydrographs and river base flows. For example, this method was used to estimate Spain's renewable reserves [3]. However, alternative calculation methods are limited, highlighting the need for further research in this area.

Currently, there are approaches for estimating reserves that include regional groundwater modeling and multi-basin water balance assessments. By combining a geological model with a 3D flow model, groundwater reserve curves can be determined as a function of piezometric level elevation, which are highly useful for supply management and can be updated as extraction progresses and new data become available (e.g., Ruiz-Constan et al., 2014) [4]. The values for drainable porosity used in these calculations are derived from dewatering estimates and numerical modeling, but they carry significant uncertainty, and their variation with depth is also poorly understood [1].

Most previous studies have focused on specific aquifer systems at a regional level, and reserves are typically calculated once the aquifer is already being exploited. The method proposed here is intended for broad evaluations across large regions, on the scale of entire countries, and under natural conditions, prior to exploitation.

Concerning the management of intensive groundwater exploitation for heavily exploited aquifers with actual or potential reserve depletion, two scenarios for planned management can be considered [5]: either continued consumption of groundwater reserves (groundwater mining) or recovery of aquifers and their levels. Wada et al. (2010) [6] attempted to rank the consumption of reserves across a broad set of global aquifers, both large and small, estimating reserve consumption as the difference between groundwater extraction and the natural recharge of each aquifer, based on bibliographic sources. Werner et al. (2013) [7] also sought to rank the degree of groundwater reserve usage by the percentage ratio of reserve consumption to extraction. This reserve consumption does not necessarily equate to groundwater mining but includes dynamic drawdown. Using integrated remote sensing, GIS, and a spatial modeling approach based on field data, dynamic reserves were assessed in a region in India [8].

1.1. Objectives of This Work

The primary objective of this study is methodological, presenting the theoretical mathematical development of a novel method to calculate renewable groundwater reserves across broad regions. This method relies on the distribution functions of water contributions from springs and representative depletion coefficients of springs, classified by lithological groups. Although applying this method to Spain is beyond the scope of this work, due to the unavailability of comprehensive spring data, the procedure is exemplified through its application to calcareous aquifers, which hold significant importance in Spain.

Natural groundwater discharge to the surface occurs primarily through springs, which give rise to rivers and streams. It can also occur as diffuse discharge that feeds rivers and lakes. Additionally, discharge may happen through transpiration or direct evaporation from the water table when it is close to the surface. Finally, local groundwater flows may emerge in small seepage areas. Any natural surface discharge with sufficient flow to form a small stream can be considered a spring, while smaller discharges are termed seepage.

It is challenging to establish a minimum flow threshold to differentiate a spring from diffuse discharge a priori. In Sanz Pérez [9], diffuse discharge for Spain was estimated by varying the lower flow limit for springs, but the total diffuse discharge into rivers was not calculated. Therefore, the method proposed here for estimating hydrodynamic or renewable groundwater reserves relies primarily on spring statistics, meaning the results obtained should be considered as a minimum estimate.

The second objective is to analyze and quantify the role played by groundwater reserves and resources in the regulation of water supply in Spain, highlighting the importance of knowing these groundwater reserves.

1.2. Terminology

Renewable resources roughly coincide with the natural recharge of the aquifer system or part of it. Exploitable resources are those feasibly extracted with acceptable conditions. This implies a decision about what is acceptable, which is a result of social and political constraints and decisions. Groundwater reserves refer to the total quantity of drainable water contained in an aquifer or aquifer systems up to a certain depth, as a result of considering the volume of groundwater in the aquifer or aquifer systems multiplied by its specific yield. Reserves can be divided into permanent water reserves (W_p) and hydrodynamic reserves (V). Hydrodynamic reserves are those located above discharge points in springs and rivers, which can flow out by gravity.

To estimate the permanent reserves (W_p) of groundwater, the volume of the saturated aquifer (V) below its outflow level (spring, river, etc.) must be cubed and multiplied by the average effective porosity (m_e). The effective porosity may vary with depth, which should be considered. This simplification is assumed given that aquifers can lose water to underlying aquifers with lower energy potential, along fault lines, and so forth, without considering the effects of pumping.

In order to cube the volume of a particular aquifer below the drainage level, it is very useful to draw a contour line or structural contour map of the base of the aquifer. The drawing of these horizontal lines can be obtained by means of the graphical representation technique of dimensioned plans. This is performed on the basis of surface geology as the main basis (geological map), with the help of data from fully penetrating boreholes in the aquifer, stratigraphic columns and layer thicknesses, information provided by geophysical surveys, etc.

Finally, by planimetry and elevations, the volume of reserves between two contour lines is calculated:

$$V_i = A_i h_i$$

with A_i being the horizontal area between two continuous lines and h_i the average height of both.

Thus, one would have:

$$V = S_i\ V_i = S_i\ A_i - h_i$$

The permanent water reserves (V_p), considering an efficient porosity would be:

$$V_p = V\ m_e$$

Hydrodynamic or renewable reserves (V) refer to the volume of groundwater stored above the natural drainage level of the aquifer at a given time (springs, rivers, etc.). Permanent reserves are below this drainage level and can only be extracted through boreholes or galleries.

On the other hand, and as is known, the discharge flow rate from an aquifer of considerable depth with constant level drainage through a spring or a hydraulically connected stream in a regime not influenced by pumping or recharge, for example, is defined by the recession depletion that can be calculated by means of an exponential type of equation:

$$Q_t = Q_0\ e^{-\alpha t}, \tag{1}$$

where Q_t is the discharge at time t, Q_0 is the initial discharge at the beginning of the recession or depletion curve ($t_0 = 0$), and the depletion coefficient is denoted by α (established by Boussinesq in 1877) [10]. The expression for the depletion coefficient, α, was given by Rorabaugh [11]:

$$\alpha \left[T^{-1}\right] = \frac{2(Kb)}{SL^2}. \quad (2)$$

This depletion coefficient depends not only on the hydrogeological parameters of the aquifer: T (transmissivity) and S (storage coefficient) but also on the geometrical characteristics of the aquifer: L is the length from the centre of gravity of the aquifer to the point of discharge and b is the mean saturated thickness of the aquifer when considering that $T = K\,b$, where $K\left[LT^{-1}\right]$ is the hydraulic conductivity.

To obtain the volume of groundwater stored in an aquifer above the spring (hydrodynamic volume or reserves) at any instant within the water recession period, it is sufficient to integrate the expression (1) between 0 and infinity.

$$V_{t0} = \int_{t_0}^{\infty} Q_t\,dt = \int_{t_0}^{\infty} Q_0\,e^{-\alpha t}dt = \frac{Q_{t0}}{\alpha} \Rightarrow V_{t0} = \frac{Q_{t0}}{\alpha}. \quad (3)$$

Equation (3) shows that α has the dimension of t^{-1}. Its value can be determined from Equation (1) through the depletion phase hydrograph as follows:

$$lnQ_t = lnQ_0 - \alpha t \Rightarrow \alpha = \frac{lnQ_0 - lnQ_t}{t}. \quad (4)$$

If a rather filled aquifer is envisaged as multiple flow layers with different depletion coefficients $\alpha_1,\ \alpha_2,\ \alpha_3,\ \ldots \alpha_n$, the expression for Q_t would be

$$Q_t = Q_{01}\,e^{-\alpha_1 t} + Q_{02}\,e^{-\alpha_2 t} + \ldots\ Q_{0n}\,e^{-\alpha_n t}. \quad (5)$$

2. Methodology

The proposed methodology for calculating the renewable reserves of a large region for an average year involves summing the hydrodynamic volumes of all springs draining the region's various lithologies. Establishing the distribution functions of water contributions based on flow rates for the lithological groups of a large region, such as Spain [12], is necessary. Subsequently, the method establishes a relationship between spring flow rates and hydrodynamic volumes, enabling the integration of these volumes as a function of the flow rate.

Basic statistical methods are used to analyze the regulatory capacity of groundwater resources and aquifer reserves in Spain. By estimating the frequency and variability of annual inflows and their alignment with water demand, the primary annual regulation role of surface reservoirs is assessed. The inter-annual regulation capacity of aquifers is quantified by estimating groundwater renewal rates and periods within hydrographic basins. All data are sourced from the Spanish MIMAN Ministry's "Libro Blanco del Agua" (2000) [13].

As mentioned above, this methodology previously relied on the distribution functions of water inflows according to flow rates for the lithological groups of a large region, which were then related to the hydrodynamic volumes. Such functions have only been established in Spain [9,12] and are described below.

2.1. Estimating Groundwater Renewable Reserves over Wide Regions Using Aquifer Lithology

2.1.1. Distribution Functions of the Hydraulic Contribution of Springs According to Flow Class, by Lithological Group

Spain spans a surface area of 505,990 km^2, encompassing a diverse range of lithologies (excluding volcanic rocks). These lithologies have been categorized into nine types based on similar hydrogeological behavior, as shown in Table 1 and Figure 1. Flow and lithology data were available for approximately 17,000 springs, covering 62% of the surface area. The general distribution function

$$a(x) = kx^{-n} \tag{6}$$

where $a(x)$ represents the discharge of all springs with flow volume x, which involves two parameters, k and n. For Spain, the sampled area with spring data yields $a(x) = 760x^{-0.91}$, where x is expressed in l/s and $a(x)$ in hm^3/year. This function has also been determined for nine lithological groups, as shown in Table 1:

Table 1. Distribution functions of the hydraulic contribution according to flows for each lithological group [12].

Lithological Group			Discharge Function	Upper Validity Limit for x	
k/10,000 km^2		km^2		$x<$	$a(x)$
31.5	Alluvial sediments	52,126	$164.0x^{-1.08}$	1500	0.06
17.7	Conglomerates	22,824	$40.4x^{-0.89}$	500	0.16
33.6	Sandstones	12,029	$40.4x^{-1.02}$	100	0.37
61.0	Limestones	59,837	$365.0x^{-0.81}$	4000	0.44
11.8	Marls	92,839	$110.0x^{-1.27}$	200	0.13
1.5	Quartzites	4935	$7.3x^{-0.88}$	50	0.23
4.5	Slates and Shales	36,395	$16.4x^{-1.18}$	100	0.07
7.5	Plutonic rocks	19,740	$14.9x^{-1.20}$	50	0.14
2.1	Other rocks	7711	$1.6x^{-0.67}$	50	0.12
24.6	TOTAL	30,8436	$760.0x^{-0.92}$	4000	0.40

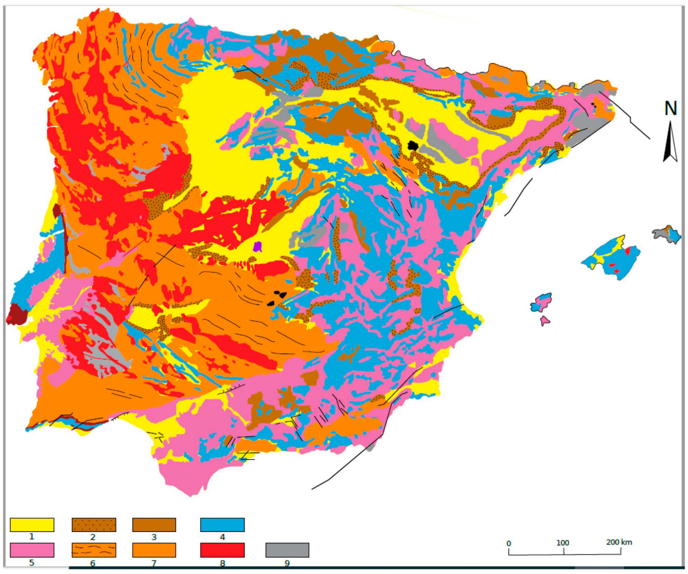

Figure 1. Schematic lithological map of the Iberian Peninsula (adapted for Spain from Riva, 1969, and Sanz de Ojeda et al., 2019 [14,15]); original scale 1:400,000. Original elaboration for Portugal in this study: (1) alluvial sediments; (2) conglomerates; (3) sandstones (differentiated only for Spain; included in 7 for Portugal); (4) calcareous rocks (limestones and dolomites); (5) silt, clay, sands, marls, and calcareous marls, generally corresponding to the large Tertiary Continental Basins of the major Spanish rivers, except the "Páramo" limestones; (6) quartzites (differentiated only for Spain; included in 7 for Portugal); (7) slates (differentiated only for Spain; for Portugal, this color represents all metamorphic rocks, including the majority of sandstones); (8) plutonic rocks; (9) other rocks (gypsum and volcanic rocks).

2.1.2. Significance of the Parameters k and n in the General Distribution Function

Expression (6) is a power function where both k and n are positive, making it a decreasing function. Its derivative, $a'(x) = -kx^{-(1+n)}/n$, is always negative, confirming the decreasing nature. The concavity is always positive, as indicated by the second derivative, $a''(x) = kx^{-(2+n)}/n(1+n)$.

This function is defined in the first quadrant, with asymptotes corresponding to the coordinate axes, given by:

$$\lim_{x\to 0} a(x) = kx^{-n} = \infty,$$

and

$$\lim_{x\to \infty} a(x) = kx^{-n} = 0.$$

The parameter k represents the hydraulic contribution from the springs for a flow of $x = 1\ l/s$ since $a(1) = k1^{-n} = k$. This parameter does not affect the shape of the function and serves as a multiplicative factor for the values of x^{-n}.

Upon plotting the function using semi-logarithmic coordinates

$$lna(x) = ln(k) - nln(x)$$

reveals that n represents the slope of the straight line (a descending slope). In our case, the absolute value of n ranges from 0.81 for limestones (the smallest) to 1.27 for marls (the largest). The parameter n holds significant importance: dividing the hydraulic contributions corresponding to two discharges in proportion (e.g., by a factor of 10) yields:

$$a(10x) = k(10x)^{-n}$$

and

$$a(x) = kx^{-n} \rightarrow \frac{a(10x)}{a(x)} = 10^{-n}.$$

Thus, for a discharge ten times larger than another, the hydraulic contributions would be reduced to the following percentages (as shown in Table 2):

Table 2. Calculation of the percentage reduction in hydraulic contribution for each lithological group as flow increases from 10 to 100.

		% of $a(x)$ for	
Lithological Group	n	$a(10x)$	$a(100x)$
Limestones	0.81	15.5	2.4
Quartzites	0.88	13.2	1.7
Conglomerates	0.89	12.9	1.7
Sandstones	1.02	9.5	1.0
Alluvia sediments	1.08	8.3	0.7
Slates and Shales	1.18	6.6	0.4
Plutonic rocks	1.2	6.8	0.4
Marls	1.27	5.4	0.3
Other rocks	0.67	521.4	4.6
TOTAL	0.91	12.3	1.5

In other words, for a discharge that is 10 times larger than another, the general hydraulic contribution will be reduced to 12.3% overall, with individual contributions ranging from 15.5% for limestones to 5.4% for marls. For a discharge 100 times larger, the mean percentage drops to 1.5%. This highlights the rapid decrease in hydraulic contributions as discharge increases.

2.1.3. Generalization of Hydraulic Contribution Distribution Functions by Flow Class

For Spain, and for each of the nine lithological groups into which the country has been divided, we established functions that describe the contribution $a(x)$ of springs with a discharge x. These functions are all of the same type, given by (6), where the parameters k and n are derived from statistical series of springs with varying mean flows and lithological characteristics.

For Spain, it is evident that the climate significantly influences natural recharge and, consequently, the mean flow of springs. We assume that for a specific lithology, the hydraulic contribution function will always follow the form (6), but with different parameters if the lithology is in a region with varying natural recharge. Analyzing the variation of these parameters in relation to variables affecting natural recharge would be valuable. In certain cases, it has been observed that for a particular lithology, there is a strong correlation between the natural recharge of aquifers and the variables of rainfall and temperature [16]. It is likely that this variability in natural recharge predominantly affects the parameter k; however, this requires further confirmation.

If this hypothesis is confirmed, the most significant conclusion would be that these functions could be applied to any other country or territory. For this application, it would suffice to know the surface area of each of the nine lithological groups, along with their rainfall and temperature data. This approach could not only be extended to other regions but could also be used to calculate annual variations within a specific country or territory based on yearly precipitation and temperature data.

Given Spain's diverse climate, we can analyze the behavior of springs within its borders across three or four zones with varying pluviometry and temperature. For each lithology, we need to establish the function (6) in these zones and calculate the mean precipitation and temperature. By doing so, the correlation between temperature (T), precipitation (P), and the parameter k can be determined.

Once the distribution of lithologies and their characteristic functions based on precipitation and temperature is established, it would be feasible to aggregate these functions for a specific country or territory. This would allow us to determine the parameters k and n for that region using the following calculations.

For $x = 1\ l/s$, we can demonstrate that

$$k = \sum_{i=1}^{9} k_i$$

since $a(1) = \sum_i k_i 1^{-n_i} = \sum_i k_i$

For another value of x, i.e., $x = x_1$, we can calculate the sum of hydraulic contributions from the various lithological groups, since we have their functions

$$a(x_1) = \sum_i k_i {x_1}^{-ni}$$

and once the hydraulic contributions are known, we can posit the equation

$$a(x_1) = k{x_1}^{-n} \rightarrow lna(x_1) = lnk - nln(x_1),$$

where

$$n = \frac{ln(k) - ln(a(x_1))}{ln(x_1)}.$$

Once this function is known, one can deduce the national water balance.

The functions obtained for the nine lithological groups in Spain, based on the same surface area of $10,000\ \text{km}^2$ for all of them, would be as follows (Table 3):

Table 3. Functions for calculating the sum of hydraulic contributions from various lithological groups, referenced to an area of 10,000 km^2.

Ground Type	$a(x_1)$
Alluvial sediments	$31.5x^{-1.08}$
Conglomerates	$17.7x^{-0.89}$
Sandstones	$33.6x^{-1.02}$
Limestones	$61.0x^{-1.27}$
Marls	$11.8x^{-1.27}$
Quartzites	$1.5x^{-0.88}$
Slates and shales	$4.5x^{-1.18}$
Plutonic rocks	$7.5x^{-1.20}$
Other rocks	$2.1x^{-0.67}$

2.1.4. Calculation of the Hydrodynamic Volume of Aquifers for Each Lithological Category

This statistic is of interest because it represents the groundwater hydrodynamic reserves that sustain river baseflow during the dry season, when surface runoff is typically absent. During periods of low rainfall, water sources are twofold: one from surface and groundwater reservoirs managed by humans, and the other from natural spring flow, which follows a declining curve (negative exponential) depending on the spring's recession coefficient. Generally, this decline is gradual, such that the rainy season begins before the discharge falls below half. This exemplifies the natural regulating power of springs.

Given that spring functions and their discharges have been established by flow class, establishing a relationship between a spring's discharge (q) and the hydrodynamic volume (V) that sustains it would enable the integration of these volumes as a function of flow. This general relationship is $q = V\alpha$, where α is the recession coefficient, and, therefore,

$$V = \frac{q}{\alpha}.$$

The coefficient α can be expressed as a function of the aquifer parameters, i.e.,

$$\alpha = \frac{\pi^2 K b}{4SL^2}$$

where K is the aquifer permeability, S the storage coefficient, b the mean saturated thickness and L the mean length of the aquifer.

We observe that the expression for α contains two distinct factors. The first, K/S, corresponds to the texture of the terrain and can be precisely evaluated for each lithological group. The second, b/L^2, is inherent to the aquifer's geometry and is undoubtedly related to its hydrodynamic volume, which is proportional to its spring discharge. To establish this relationship, we must assume that, during the onset of the depletion phase, the gradient $i = b/L$ remains nearly constant and can be considered fixed.

This case of hydrodynamic volume can be expressed by

$$V = \frac{1}{2}L^2 b = \frac{1}{2}L^3\frac{b}{L} = \frac{1}{2}L^3 i$$

from which we find that

$$L = \sqrt[3]{\frac{2V}{i}},$$

where

$$V = \frac{q}{\alpha} = q\frac{4SL^2}{\pi^2 K b} = q\frac{4SL}{\pi^2 K i} = q\frac{4S}{\pi^2 K i}\sqrt[3]{\frac{2V}{i}}.$$

By solving for V in the above equation between the first and last members, we obtain

$$V^{(1-\frac{1}{3})} = V^{2/3} = \frac{4S\sqrt[3]{2}}{\pi^2 Ki\sqrt[3]{i}}q$$

or

$$V = \sqrt{\left(\frac{4S}{\pi^2 Ki}\right)^3 \frac{2}{i}}\, q^{3/2}.$$

This expression applies to a specific discharge q and the fixed values beneath the square root. If we denote by m_j

$$m_j = \sqrt{\left(\frac{4S}{\pi^2 Ki}\right)^3 \frac{2}{i}} = \sqrt{\frac{0.13}{i^4}\left(\frac{S}{K}\right)^3}$$

We consider lithology type j to be intrinsic, identifying q with the mean discharge (used for classifying the springs). Assuming this mean flow approximates the spring's discharge at the onset of the dry season, for a spring in lithological group j and aquifer q_i, we obtain

$$V(j, q_i) = m_j\, {q_i}^{1.5}. \tag{7}$$

Multiplying this value by the number of springs within the same flow class and lithology q_i, denoted as $m_j(q_i)$, yields the total hydrodynamic volume of these springs:

$$V_t(j, q_i) = m_j q_i^{1.5}\, n_j(q_i).$$

In this case, we know that $n_j(q_i)$ can be expressed as

$$n_j(q_i) = k_j {q_i}^{-n_j}, \quad 0 < n_j < 1.5$$

so

$$V_t(j, q_i) = m_j\, k_j q_i^{1.5-n_j}$$

will be a potential function with a positive exponent of less than 1.5, since, subtracting 1.5, the inequalities $0 < n_j < 1.5$ become $1.5 > 1.5 - n_j > 0$.

Summing the corresponding hydrodynamic volumes for all discharges within lithology j results in

$$V(j) = \sum_i V_t(j, q_i) = m_j k_j \sum_i q_i^{1.5-n_j}$$

The continuous, integrated form of this expression is

$$V(j) = m_j\, k_j \int_0^{q_i(max)} q_i^{1.5-n_j} dq_i = \frac{m_j k_j}{2.5 - n_j}[q_i(max)]^{2.5-n_j} \tag{8}$$

This expression represents the sum of the hydrodynamic volumes for all springs whose aquifers correspond to lithology j. The values of k_j, n_j, and $q_i(max)$ have been previously studied and determined for each lithological group. As for m_j, we return to function (7), which pertains to a single spring:

$$V(j, q_i) = m_j q_i^{1.5}$$

If we can determine α and thus $V(j,\ q_i)$ for one or more springs within lithology j, then for a mean flow q_i, using the expression $V = q/\alpha$, we can obtain

$$m_i = \frac{V(j, q_i)}{q_i^{1.5}}$$

Hence, all the parameters of expression (8) are known.

3. Results and Discussion: Importance of Groundwater Reserves and Resources in the Regulation of Water Supply in Spain

3.1. Application of the Proposed Method to Spain

As stated in the objectives (Section 1.1), this method builds on spring statistics, and therefore, strictly speaking, it calculates the hydrodynamic reserves associated with aquifers drained by springs (appreciable water outflows that, according to Meinzer (1942) [17], would have a lower limit of 0.5 L/min). Thus, the method calculates a volume of minimum hydrodynamic reserves, as it does not account for diffuse discharges into streams, rivers, or the sea. However, Sanz (2001) estimated discharges below this limit for Spain [9], amounting to a significant volume (slightly over 5000 hm^3/year), which could potentially be attributed to a portion of the diffuse discharges into streams and rivers.

The theoretical method proposed here would require a series of average discharge rates from springs representative of each lithology, which are currently unavailable to us. Perhaps it could be attempted with the springs from the limestone lithology, where the springs are more significant. For instance, consider a substantial group of springs representative of the 'limestone' lithology, where it is known that for an initial depletion discharge rate of $q_i = 800$ l/s, $V\left(23\ \text{km}^2\right) = 23 \times 10^9$ l. Then, we can employ this value for this lithology:

$$m_j = \frac{23 \times 10^9}{800^{1,5}} = 10.134 \times 10^3$$

and since the parameters of the limestone lithology are

$k_j = 11.527$; $n_j = 1.81$, and $q_j(max) = 4000$ l/s, it results in

$$V(j) = \frac{10.164 \times 10^3 \times 11.527}{2.5 - 1.81} 4000^{0.69} = 52.011 \times 10^9\ \text{l} = 51.025\ \text{hm}^3,$$

which is the approximate hydrodynamic volume of all the springs within the limestone lithology at the beginning of the low-flow period, i.e., 53 km^3, representing 59% of the total estimated renewable or hydrodynamic reserves of 86,118 hm^3, according to [3].

3.2. Surface Reservoirs in the Regulation of Water Supply and Hydrological Variability in Spain

According to MIMAM (2000) [13], the source of all the data discussed below, the total contribution of useful rainfall in Spain is distributed as shown in Table 4.

Table 4. Distribution of the total contribution of useful rainfall in Spain (MIMAM, 2000) [13].

Total Contribution	Aquifer Recharge	Runoff
111 km^3	29 km^3	82 km^3

Of this river runoff, only 16 km^3 is naturally regulated: 9 km^3 for consistent demands (primarily for urban consumption) and 7 km^3 for variable demands (such as irrigation). This regulation is largely due to the base flow of rivers, which originates from underground sources.

However, given the substantial gap between water demand and availability over the hydrological year, efforts have been made to enhance water regulation by constructing surface reservoirs to store excess water. Spain currently has a storage capacity of 47 km^3 per year in these reservoirs, which supports a uniform demand of 36 km^3 per year and a variable demand of 39 km^3. This results in a total demand of 75 km^3 per year, which is 1.6 times the reservoir capacity. Additionally, approximately 5.5 km^3 per year is extracted from aquifers.

On the other hand, Spain is characterized by significant hydrological variability and irregularity, largely influenced by its diverse climate. This variability encompasses both temporal and spatial factors. Within the temporal aspect, it is important to differentiate between intra-annual seasonal variations and inter-annual variations.

Seasonal variations are particularly crucial for regulation plans, as reserves need only be managed for short periods, typically less than a year. Notably, disparities between inflows and demands are pronounced across different seasons. Inflows generally increase from October to February and are sustained until April, while demand, which includes a consistent year-round component, experiences a significant rise between May and August. However, variations in both inflows (e.g., snowmelt) and demand (e.g., reduced agricultural consumption) may occur, necessitating specific analysis for the area in question. As previously noted, managing intra-annual regulation tends to incur the lowest cost for storing excess water.

Surface reservoirs are primarily designed to align supply with the seasonal variations in demand for the basins or areas they serve. They typically use the average annual inflow over several years as a benchmark for resource management. However, interannual inflow distribution is highly variable and unpredictable. As a result, there are years in which the reservoir may not reach full capacity, leading to challenges in meeting demand. Conversely, in other years, inflows may exceed reservoir capacity, causing substantial volumes of water to be lost.

The series of annual contributions over a 55-year period, as detailed in the "Libro Blanco del Agua" (MIMAM, 2000) [13], form the basis for the creation of Figure 2 and Table 5, which display the frequency distributions. The corresponding statistical parameters are outlined in Table 6.

Regarding the mean of 111 km^3/year, the notable high standard deviation of 39 km^3/year and the positive skew coefficient of 0.65 indicate a departure from a normal distribution. This suggests more frequent periods of low rainfall—occurring in 60% of the years—while the remaining 40% of years experience above-average rainfall.

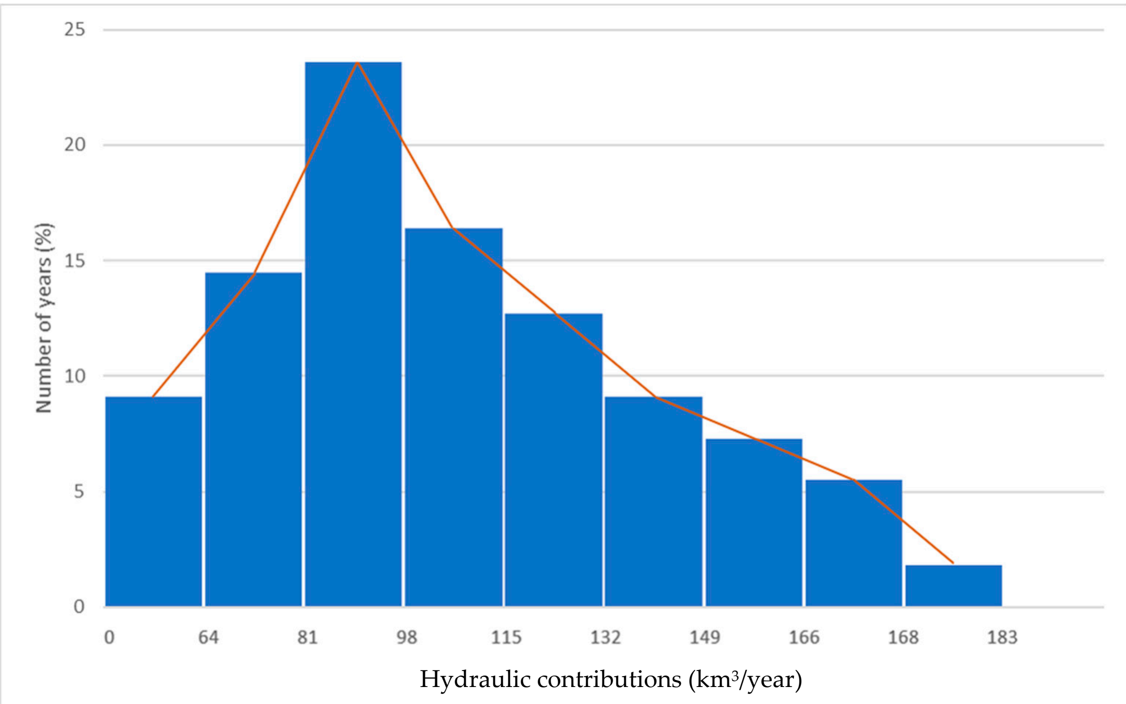

Figure 2. Frequency distribution of the annual hydraulic contributions in Spain.

Table 5. Frequencies of annual hydraulic contributions (compiled from MIMAM, 2000 Data) [13].

Water Contributions	Years
km^3/year	(%)
Less than 64	9.1
64–81	14.5
81–98	23.6
98–115	16.4
115–132	12.7
132–149	9.1
149–166	7.3
166–183	5.5
More than 183	1.8
Total	100

Table 6. Characteristic statistical parameters of the series of annual hydraulic contributions as shown in Table 5.

Statistical Parameter	Value
Average	111 km^3/year
Maximum	247 km^3/year
Minimum	50 km^3/year
Maximum/minimum	4.9 km^3/year
Standard deviation	39 km^3/year
Coefficient of variation	0.35
Coefficient of bias	0.65

Consequently, a hypothetical reservoir designed to regulate 111 km^3 of water annually would provide less than 90% of the demand in 47% of the years. Conversely, during 40% of the years with higher-than-average contributions, the reservoir would experience an annual excess of 12.5 km^3. Over a century, the total demand would amount to 11,100 km^3, while the supply would be 9849 km^3 after a reduction of 1251 km^3, thereby covering 89% of the total demand.

By increasing the reservoir capacity to 132 km^3, which represents a 19% increase over the average contribution, the theoretical loss during the rainiest years would be reduced to 581 km^3. Consequently, the supply would rise to 10,519 km^3, covering 95% of the demand. This means that a 19% increase in reservoir capacity results in only a 6.8% increase in supply.

Expanding the capacity of a surface reservoir to enhance the probability of meeting a given demand involves significant economic considerations. The marginal return on substantial investments must be carefully evaluated. Surface reservoirs require design, construction, and filling. In contrast, aquifers are naturally formed and already filled (assuming they are not overexploited). Although detailed studies are necessary to understand their characteristics, aquifers do not require expansion. They can better accommodate variations in supply and demand, providing crucial support during dry years and absorbing excess water from wet years.

While the above values represent national annual averages, it is crucial to consider the spatial factor, which is particularly significant in Spain due to its hydrological variability. Table 7 presents basic statistics on the average annual contributions for each of the designated territorial areas (see Figure 3).

The irregularity of these contributions becomes evident when expressed relative to the surface area (l/m^2), ranging from 933 l/m^2 in the Galician Coast and Norte III to 42 l/m^2 in the Segura River basin. In this context, four nearly homogeneous regions with distinct statistical parameters can be identified within the Spanish Peninsula (Table 8).

Table 7. Annual hydraulic contributions in the main Spanish river basins.

Territorial Scope	Surface km^2	Annual Inputs (km^3)					Variation	Variation	%
		Minimum	Medium	Maximum	Max/Min	n /m^2	Rate	Bias	Water Refill
North I	17,600	5.1	12.7	24.1	4.8	721	0.38	0.68	22
North II	17,330	6.3	13.9	21.7	3.5	801	0.22	−0.15	37
North III	5720	2.2	5.3	8.7	4.0	933	0.24	−0.13	18
Duero	78,960	4.9	13.7	30.4	6.2	173	0.47	0.80	22
Tajo	55,810	2.5	10.9	30.7	12.4	195	0.56	0.75	22
Guadiana I	53,180	0.3	4.4	12.4	47.8	83	0.81	0.67	16
Guadiana II	7030	0.1	1.1	3.7	30.6	151	0.88	1.01	6
Guadalquivir	63,240	0.4	8.6	26.2	60.0	136	0.77	0.91	27
Sur	17,950	0.1	2.4	7.3	59.6	131	0.71	1.35	29
Segura	19,120	0.3	0.8	1.7	5.9	42	0.36	1.00	73
Júcar	42,900	1.6	3.4	6.7	4.3	80	0.34	0.79	73
Ebro	85,560	8.8	18.0	32.8	3.7	210	0.29	0.57	26
C.I. Cataluña	16,420	6.9	2.8	7.0	*TI*	170	0.54	0.93	33
Galician Coast	13,130	5.4	12.3	21.1	3.9	933	0.33	0.35	18
Peninsula	494,120	50.2	110.1	221.2	4.4	223	0.35	0.66	26
Balearic Islands	5010	0.2	0.7	2.3	13.2	132	0.63	1.59	-
Canary Islands	7440	0.0	0.4	1.3	35.2	55	0.72	1.51	
SPAIN	506,470	50.4	111.2	224.8	4.4	220	0.35	0.65	

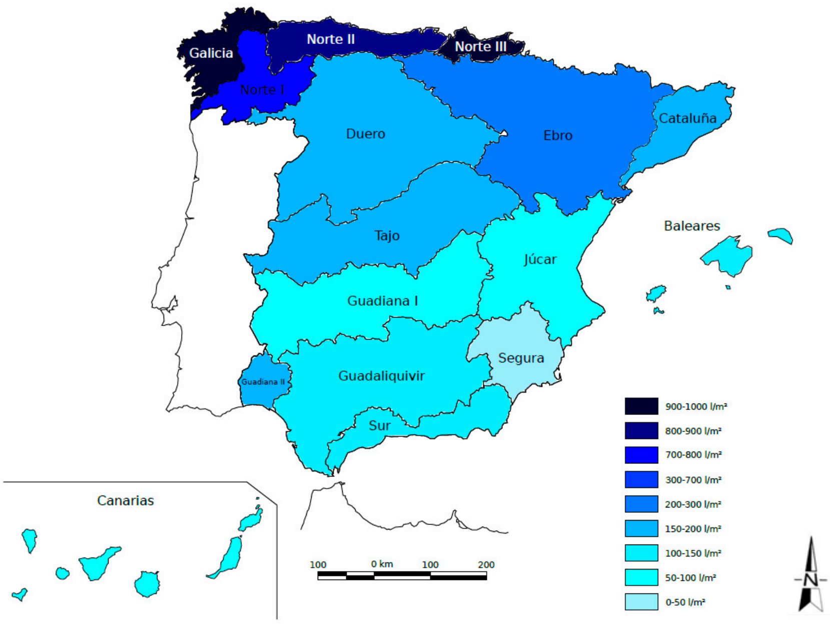

Figure 3. Medium annual hydraulic contributions in the Spanish river basins (in l/m^2).

Table 8. Average values of the annual hydraulic contributions for groups of river basins.

Region	Input (l/m^2)	Variation Rate	Variation Bias	Water Refill (%)
Cantabrian Coast	820	0.30	0.35	25
North (Duero, Tajo, Ebro and Catalonian basins)	193	0.42	0.70	24
Guadiana, Guadalquivir and Sur	116	0.78	0.91	22
Júcar and Segura	68	0.34	0.83	73

The following observations pertain to variability within each of these four regions:

On the Cantabrian coast, the variation coefficients in its four zones are generally lower than the national average, with the exception of Norte I, which is part of Lower Galicia (see Table 7). This indicates that not only are the contributions significantly higher in this region, but they also exhibit more consistent patterns throughout the year, with a distribution that is closer to normal. This is reflected in a smaller absolute value of the skew coefficient, unlike in Norte II and III, where negative values are observed.

Additionally, the proportion of water inputs that contribute to aquifer recharge is somewhat lower than the national average, due to a higher fraction of surface runoff. This exception is found in Norte II, where the presence of carbonate lithologies results in a greater recharge of aquifers.

In the remaining northern regions (Duero, Tajo, Ebro, and Inner Basins of Catalonia), annual contributions are approximately 200 l/m^2, which is higher than in the southern and Levante regions but less than a quarter of the amounts observed on the Cantabrian Coast. Additionally, the irregularity throughout the year is significantly greater, as evidenced by an average coefficient of variation of 0.70, compared to 0.35 on the Cantabrian Coast.

As one moves south, both the volume of unit input and its irregularity show a notable trend: the average annual contribution in the Guadiana, Guadalquivir, and Southern basins is 116 l/m^2. Here, both the coefficient of variation (0.78) and the skew coefficient (0.91) are the highest among the four regions.

In the Levante region (Júcar and Segura rivers), the contribution is notably low at 68 l/m^2, which is about one-third of the national average and one-twelfth of that on the Cantabrian Coast. Despite the annual variability in rainfall being similar to that of the southern regions, the contribution variability is markedly lower (coefficient of variation of 0.34). This reduction is attributed to the significant role of aquifers in regulating rainfall, which leads to a recharge rate of 73%—three times higher than in other zones.

3.3. Aquifers and Their Regulatory Capacity

It is generally accepted that the water resources of a geographical area include both its renewable resources (surface and groundwater). In addition to these renewable resources, aquifers often contain substantial reserves of water that may take years to replenish. Under natural conditions, these reserves are considered a form of permanent storage. However, under influenced conditions, these reserves can provide increased temporary availability, potentially enhancing long-term resource levels.

Therefore, when discussing the water in underground reservoirs or aquifers, it is important to make a distinction:

On the one hand, there are the reserves, which refer to the volume of groundwater that is readily accessible at a given time. These reserves are primarily determined by the aquifer's total volume and its effective porosity.

On the other hand, resources refer to the volume of water that can be sustainably extracted annually, taking into account the need for conservation and protection as well as technical and economic constraints. Generally, resources represent only a portion of the reserves. However, in some aquifers with high inflow rates and permeability, the available resources may exceed the reserves.

Renewable reserves and permanent reserves can be considered separately, with their sum representing the total reserves at a given time. Distinguishing between these two types of reserves requires accounting for seasonal and inter-annual variations in the water table.

For resources, the average annual inflow over a long period—typically exceeding 10 years—is used. During this period, the mean annual recharge I_w is assumed to be equal to the mean annual flow Q_w, implying no net change in the stock. Thus, these values ($Q_w = I_w$) are identified as the renewable reserves (V) of the aquifer. It is important to note that this does not imply that such a volume of water is continuously present, as it is subject to inflows and outflows throughout the year.

In addition to the renewable reserves, there are permanent reserves (W_p). Consequently, the total reserves (WT) assigned to the aquifer are the sum of both types: $T = V + W_p$.

The ratio of these reserves is crucial for assessing the aquifer's regulatory capacity. This ratio is often expressed as the "Annual Renewal Rate" (ARR) [18,19], defined by the quotient

$$TRA = V/WT = I_w/WT = Q_w/WT.$$

Additionally, the inverse of this ratio is known as the 'Renewal Period in Years' (PRA), which represents the time required to deplete all of the aquifer's reserves while maintaining natural replenishment rates

$$PRA = WT/V.$$

This rate and period exhibit significant variability across different aquifers. The renewal rate can range from values close to 1 to less than one thousandth, resulting in corresponding renewal periods ranging from less than a year to several millennia. For instance, Castany (1975) [18] provides examples of real-world cases: the greensand aquifer in the Paris Basin has a renewal rate of 0.005 and a renewal period of 2000 years; the Pliocene Meknes-Fez basin in Morocco has a rate between 0.1 and 0.5, with a renewal period of 10 to 20 years; and the Inkermann alluvial sub-flow aquifer in Russia has a rate of 0.7 and a renewal period of 1.5 years. The significance of these reserves and the regulating capacity of the aquifer, based on the renewal rate values, are described by Margat (1966) [19], as depicted in Table 9.

Table 9. Importance of groundwater reserves and aquifer regulatory capacity based on renewal rate values (Margat, 1966) [19].

Renewal Rate	Reserve Importance	Regulatory Capacity
≈1	Weak	Null
≈0.5	Medium	Can be used multiannually
≈0.1	Important	Good, annual and multiannual
<0.1	Fossil	Very large

Table 10 presents estimates of annual recharge and reserves for the geographical basins of peninsular Spain, with the reserve values based on MIMAM (2000) estimates [13].

Table 10. Annual Groundwater Reserves and Resources in Spain (Based on MIMAM, 2000 Data [13]).

Basin	Groundwater Reserves	Annual Natural Recharge	Annual Renewal Rate	Renewal Period
	(km^3)	km^3/year		(Years)
Norte	7.7	10.9	1.42	0.7
Duero	43.6	3.0	0.07	14.5
Tajo	4.7	2.4	0.2	5.0
Guadiana	2.8	0.8	0.05	18,8
Guadalquivir	11.5	2.3	0.21	4.8
Sur	5.6	0.7	0.12	8.0
Segura	20.0	0.6	0.03	33.3
Júcar	79.1	2.5	0.03	31.6
Ebro	12.8	4.6	0.36	2.8
C.I. Cataluña	12.6	0.9	0.07	14.0
TOTAL	219.4	28.7	0.13	7.6

In inland Spain, the Duero and Guadiana basins are notable for the regulatory power of their aquifers, with renewal periods exceeding 14 years. Particularly significant is the good average regulatory capacity of aquifers in regions that, despite being large water consumers, experience scarce and highly irregular recharge. This includes the Levante area (Júcar and Segura) with a renewal period of over 30 years, the Internal Basins of Catalonia with a 14-year renewal period, and the Southern basin with an average renewal period of 8 years.

For all peninsular aquifers combined, it is estimated that the total reserves (WT) amount to 219 km^3 and renewable reserves (V) to 29 km^3, resulting in average values of:

- Renewal rate: 0.13 years
- Renewal period: 7.6 years

These averages indicate that many aquifers, except those on the Cantabrian coast, have substantial reserves, allowing for effective regulation both annually and interannually.

In Spain, under natural conditions, groundwater resources, estimated at 29 km^3/year, are 1.8 times greater than surface water resources (16 km^3/year). However, to meet demand, priority has traditionally been given to the use and regulation of surface water.

Besides economic considerations and factors such as underground storage and reduced evaporation losses, one significant advantage of groundwater is the 'permanent reserve'. This reserve offers a reliable means to meet demand during years of low rainfall.

It is important to note that a key characteristic of underground reservoirs is their 'inertia' to recharge or discharge impulses. This is because the active reserves are those located above the outflow levels. Even during dry years, when it becomes necessary to pump a flow exceeding the natural recharge, the impact of the aquifer's discharge will take time to manifest.

4. Conclusions

The first part of this paper aims to contribute to the development of a theoretical method for estimating hydrodynamic reserves. This method could be applied relatively easily if data on the characteristic depletion coefficients of representative springs for each lithological group with similar hydrogeological behavior were available.

The second part quantifies the role of groundwater reserves and resources in regulating water supply in Spain, where groundwater plays a key role in regulating water supply, not only for managing annual variations, which are primarily addressed by surface reservoirs, but especially for managing inter-annual variations.

Understanding the reserves of the main aquifers is essential for developing proactive action plans in case of emergencies, particularly in hydrographic basins most vulnerable to droughts. Current estimates of permanent reserves are preliminary and only consider depths up to 200 m. However, a more accurate estimate of the total permanent reserves in Spain is feasible, given the ample surface and deep geological data from hydrocarbon investigations, as well as sufficient hydrogeological information.

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