



Emilio Custodio: a pioneer in groundwater management and key reference for hydrogeologists worldwide

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Introduction

Professor Emilio Custodio is honoured as a crucial figure in modern hydrogeology. His extensive contributions to the field, both in academia and practical applications, have left an indelible mark on water resource management globally. Through his pioneering research, leadership roles, and dedication to education, Professor Custodio has been fundamental in advancing the scientific understanding and ethical governance of groundwater resources. His work continues to inspire and guide hydrogeologists around the world.

Biography

Emilio Custodio was born in Barcelona, Spain, in 1939, the year that the Spanish Civil War ended. He completed his primary school education in Solsona and attended secondary schools in Granollers (Piarists) and Barcelona (Claretians). He pursued higher education at the *Escuela de Ingenieros*

Industriales (School of Industrial Engineering) at the old Polytechnic University of Barcelona, where he graduated as the first in his class as an industrial engineer during the “intensification” of chemistry in 1964. He later specialized in nuclear engineering and completed his doctorate in 1972. In 1973, he started his career as an associate professor at the *Universidad de Tecnología Nuclear* (Nuclear Technology University) in Barcelona. He joined the *Universitat Politècnica de Catalunya* (Polytechnic University of Catalonia), UPC, as an associate professor in 1981, and became a full professor in 1986. He remained an academic throughout his entire life, continuing after his retirement in 2010 as an emeritus professor. Outside of academia, he worked as an engineer from 1964 to 1985 at the *Ministerio de Obras Públicas* (Ministry of Public Works), in the *Dirección General de Obras Hidráulicas* (General Directorate of Hydraulic Works) and in the *Comisaría de Aguas del Pirineo Oriental* (Eastern Pyrenees Water Commissioner), later transformed into *Junta d'Aigües* (Water Board), and finally to *Agencia Catalana del Agua* (Catalan Water Agency). Between

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1997 and 2004, he was appointed as director of the *Instituto Geológico y Minero de España* (IGME, Geological and Mining Institute of Spain; Fig. 1), an institution comparable to a national geological survey. During this period, under Professor Custodio's leadership, the IGME reformed into a research and development institution, which gave it an international dimension. Professor Custodio was frequently invited as an expert to numerous technical meetings organized by the United Nations Educational, Scientific and Cultural Organization (UNESCO), the International Atomic Energy Agency (IAEA) as well as other global organizations. Recognized for his leadership, he often chaired these meetings (Fig. 2). His active participation played a vital role in creating several key publications that introduced new methods and strategies for evaluating and managing water resources. He was also the founder, director, and teacher of the *Curso Internacional de Hidrología Subterránea* (International Groundwater Hydrology Course), CIHS, a post-graduate university course equivalent to a master's degree. The CIHS was the school of preference for many Spanish-speaking hydrogeologists, and had a major impact on the development of the Ibero-American hydrogeological community. Many current university professors, high-level



Fig. 1 Portrait of Professor Emilio Custodio in 2004 as general director of the *Instituto Geológico y Minero de España* (Geological and Mining Institute of Spain), painted by Juan Ignacio Burguete Albalat. It is a tradition to make a painting of the outgoing director of the institution, which is exhibited along with former directors



Fig. 2 Professor Emilio Custodio speaking in the *Jornada Nacional de Comunidades de Usuarios de Aguas Subterráneas* (National Conference of Communities of Groundwater Users) held in Prat de Llobregat in 1986. Photo taken from the archive of the *Comunitat d'Usuaris d'Aigües del Delta del Llobregat* (Community of Water Users of the Llobregat delta), which organized the conference

government managers and senior professionals in Spain, Portugal and Latin America are CIHS alumni.

Relationship with the International Association of Hydrogeologists (IAH)

Professor Custodio has always been highly committed to the International Association of Hydrogeologists (IAH) since he first joined in 1974. In the periods 1980–1984, 1996–2000, and 2004–2009, he served as a member of the IAH board of directors, eventually becoming president in 2000–2004. He made significant contributions to the scientific and organizational development of the association and received the IAH Presidents' Award in 1998. He was distinguished as an honorary member of the IAH in 2014 and of the IAH Spanish national chapter—*Asociación Internacional de Hidrogeólogos – Grupo Español* (AIH-GE)—in 2016.

During his tenure as IAH president, he worked tirelessly to promote IAH's mission and to expand its presence in Latin America, seeking collaboration with the *Asociación Latinoamericana de Hidrología Subterránea para el Desarrollo* (Latin American Association of Groundwater Hydrology for Development), ALHSUD. He made substantial contributions to the organization of the joint IAH and ALHSUD congresses in Mar del Plata, Argentina, in 2002 and in Zacatecas, Mexico, in 2004. Professor Custodio also actively advocated the creation of IAH national chapters in Argentina, Brazil, Chile, Colombia, Mexico, and Perú.

Earlier, he had chaired an IAH Spanish group (1980–1984) culminating in the creation of the IAH Spanish chapter, of which he was president (1994–1998). During

this period, Professor Custodio made an enormous effort in organizing and convening scientific meetings. It should also be noted that Professor Custodio promoted the creation of an IAH national chapter in Portugal.

Awards and recognition

Professor Custodio received numerous awards and distinctions throughout his prolific career for his outstanding scientific contributions to the field of hydrogeology, his dedication to mentoring and education, and the personal attributes and values that made him such a dear person to so many.

In 1989, he was elected as a Member of the *Real Academia de Ciencias Exactas, Físicas y Naturales* (Spanish Royal Academy of Exact, Physical, and Natural Sciences). There, he worked jointly with Professor Ramón Llamas, his former mentor, PhD supervisor and dear friend, in the defence of hydrogeology as a multidisciplinary science.

Professor Custodio especially appreciated the honorary doctorates bestowed upon him by the Argentinian universities *Universidad Nacional de Tucuman* (National University of Tucuman) in 1995, the *Universidad del Litoral* (University of Litoral) in 2005, and the *Universidad Nacional de La Pampa* (National University of La Pampa) in 2009.

He received numerous awards for his impact on the global scientific community, including the *Generalitat de Catalunya* (Government of Catalonia) Narcís Monturiol medal (1996) and the lifetime member award (for individuals who have made an exceptional contribution to the promotion of groundwater) of the National Groundwater Association (NGA) of the United States (2005). ALHSUD declared him an *illustrious hydrogeologist* of Latin America in 2008, and the *Asociación Mexicana de Geohidrología* (Mexican Geohydrological Association) organized a tribute to him as a mentor of hydrogeologists in 2012. In Spain, the *Asociación de Usuarios de Aguas Subterráneas de Tenerife* (Groundwater Users' Association of Tenerife) awarded Professor Custodio the *Cámara Insular de Aguas de Tenerife* (Island Chamber of Waters of Tenerife) in 2015, while, in 2018, the *Grupo Especializado de Aguas de la Asociación Nacional Española de Ingenieros de Minas* (Specialized Water Group of the National Association of Mining Engineers) awarded him the XIV *Carlos Ruiz Celaá* award for his professional career.

In 2011, AIH-GE organized an event in his honour and the book *Cuatro décadas de investigación y formación en aguas subterráneas* (Four decades of research and training in groundwater) was presented as a tribute. The book featured contributions from a wide range of researchers and collaborators, who provided both biographical sketches of Professor Custodio and scientific-technical chapters.

Academic legacy

In 1967, jointly with Professor Llamas and under the umbrella of the International Hydrological Decade of UNESCO (1965–1974), Professor Custodio founded the CIHS in Barcelona (Spain), which was endorsed by the UPC. The leadership comprised professionals from the *Ministerio de Obras Públicas* (Ministry of Public Works) and *Aguas de Barcelona* (Barcelona Waters) and the course quickly gained recognition as a global reference for hydrogeologists, especially in Spanish-speaking countries.

In 1990, Professor Custodio initiated the official MSc Program in Groundwater Hydrology at UPC and, in 1991, he founded the private foundation *Centro Internacional de Hidrología Subterránea* (International Center for Groundwater Hydrology, FCIHS) in Barcelona, serving as director until 1997. From 1997 to 2004, he served as a member of the foundation's board of trustees. A total of 54 editions of the CIHS were conducted during the period of 1967–2020, along with 20 editions (2003–2021) of the online version, two semipresential editions in Argentina, and ten editions (2012–2021) of the *Master Professional de Hidrología Subterránea* (Master of Groundwater Hydrology, MPHS). All these programs took place at the UPC facilities. CIHS trained over 1600 hydrogeologists, making it the longest-standing post-graduate course among all Spanish universities. The CIHS became very successful, leading to an increased interest from water professionals in Latin America to join this specialized course. This interest prompted the creation of a shorter version of the one offered in Barcelona. Since 2000, the *Curso Hispanoamericano de Hidrología Subterránea* (Latin American Groundwater course), a Latin American edition of the course, has been taking place every 2 years in Montevideo, Uruguay. Professor Custodio lectured at all 54 editions of the CIHS and also at several editions of the Latin American version. After the closure of FCIHS, Professor Custodio actively collaborated in the preparation and teaching of the master's course in hydrogeology held at the University of Barcelona during the last 2 years of his life.

One remarkable aspect of Professor Custodio's contribution to the field of hydrogeology is the book *Hidrología Subterránea* (Groundwater Hydrology; Custodio and Llamas 1976; Fig. 3), edited in 1976 and 1983, of which he was a coeditor along with Professor Llamas as well as the author of most of the chapters. This comprehensive textbook spanned over 2400 pages across two volumes and was created to help educate future hydrogeologists.

His prolific scientific work included over 700 publications (including more than 130 in scientific and technical journals, and over 40 book chapters) as well as the supervision or cosupervision of 27 doctoral theses and 12

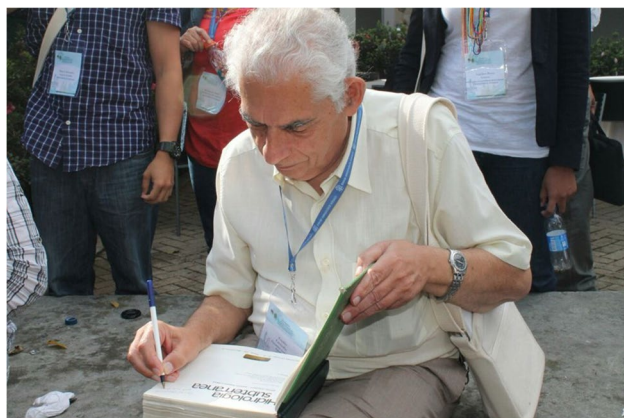


Fig. 3 Professor Emilio Custodio signing his famous book *Hidrología Subterránea* (Groundwater Hydrology; Custodio and Llamas 1976). Photo taken by Teresita Betancur in the V Congreso Colombiano de Hidrogeología (Colombian Groundwater Congress V) held in Medellín (Colombia) in 2014

master's theses. Additionally, he authored or coauthored at least 13 books and served as an editor or coeditor for 17 others.

Professor Custodio's passion for groundwater was evident from his teaching and contribution to the development of hydrogeology into a scientific and technological field. His interest in different cultures and their history led him to many parts of the world with complex water-related social management issues. He played a key role as a distinguished expert during the inaugural United Nations Water Conference held in Mar del Plata (Argentina) in 1977. Following this significant event, a strong connection was forged with professionals throughout Latin America, promoting understanding, rational use, and protection of groundwater resources.

His practical legacy and his ethics in water management, putting science to good use where it mattered, are broadly recognized amongst his peers across the globe. Professor Custodio's interests were wide, and a detailed description is far beyond the scope of this profile. The focus here will be on six key areas that were pursued over most of his career: isotopic and hydrochemical studies, coastal aquifers, groundwater recharge, volcanic aquifer, aquifer management, groundwater governance and hydroethics. The complete version of the following sections, including full references to the individual research studies, can be found in the electronic supplementary material (ESM).

Hydrochemical and environmental isotope studies

Professor Emilio Custodio is recognized as a leading geoscientist for the development and application of hydrochemical and isotopic techniques in evaluating the physical and

chemical dynamics of a wide range of groundwater systems. He led the incorporation of hydrochemistry and environmental isotopes as research tools in hydrogeological studies in the late 1960s when he completed his PhD on "Groundwater dating: dating with radioisotopes, variation of isotopic ratios and pure chemical characteristics: application to the Llobregat River Delta". Since then, he proceeded to apply hydrochemical and isotopic techniques in the majority of his works, promoting their use in both hydrogeological research and industry.

Most of his studies were devoted to understanding aquifer functioning at the regional scale, characterizing the origin of water and the processes affecting its quality. This approach helped him to account for all of the processes involved in the aquifer water balance, uncovering the origin of groundwater and controls governing chemical and quality status, and forecasting the impacts of climate change and intensive groundwater use on the natural flow and chemical quality in aquifers.

Other studies focused on the evaluation of particular hydrogeological processes. His work related to coastal aquifers and groundwater recharge will be commented on in two separate sections in the following. Beyond the characterization of physical hydrogeological systems, he applied hydrogeochemical and isotopic tools to study groundwater pollution and decontamination. In fact, his works contributed to the understanding of the impact of atmospheric deposition on groundwater salinity.

Especially fruitful were his applications of hydrochemistry and isotopes to study the environmental role of groundwater. Coupling these tools with his command of hydraulics provided clear insights into the functioning and ecology of groundwater-dependent surface-water bodies. This understanding led Professor Custodio to establish the scientific basis for various conceptual approaches and methodologies.

In summary, Professor Custodio's hydrochemical and environmental isotope research had very diverse objectives and encompassed different hydrogeological contexts. He always used his aforementioned techniques in a pedagogic way, developing methodologies that would be further developed by many researchers and professionals, especially in Spain and Latin America.

Coastal aquifers

Professor Custodio contributed extensively to the scientific understanding and practical management of coastal aquifer systems, both in natural and perturbed conditions across diverse settings and contexts. His studies on this topic started in the late 1960s with the aquifers of the Delta del Llobregat (Spain). An initial article, dating to 1970, focuses on marine intrusion in this area. Throughout his career, he authored numerous works in the form of articles in scientific

journals, conference proceedings—Salt Water Intrusion Meeting (SWIM), IAH, International Symposium on Managed Aquifer Recharge (ISMAR), etc.—studies, reports, and books. He led various projects in the Mediterranean and various islands, predominantly in volcanic settings such as the Canaries, Easter Island (Chile), Doñana area, and also worked in Europe and Latin America. In more recent times, his research extended to the study of the saline interface in Andean Salt Flats.

His works spanned from basic characterization to conceptualization, monitoring, assessment, tracing contaminants, modelling, remediation, management, etc. In essence, he comprehensively addressed all relevant aspects of coastal aquifers during his career.

Furthermore, his role as an educator in hydrogeology played a critical role in developing a skilled human resource pool and transmitting aspects related to coastal aquifers to society. Specifically, his profound legacy includes a generation of hydrogeologists in Europe and Latin America capable of navigating, teaching, and communicating aspects related to the research, characterization, and management of coastal aquifers in various contexts and situations.

Recharge studies

Professor Custodio made numerous and relevant contributions to the study of groundwater recharge, both natural and artificial. His work on the use of environmental tracers, which enter aquifers during recharge and exit during discharge, is of particular interest. This approach enabled the estimation of recharge in peninsular Spain within a geo-statistical framework for the first time.

Professor Custodio focused his interests on alpine hydrogeological systems, where snowmelt contributions to groundwater recharge were particularly challenging to understand. He developed a series of analytical methods for estimating recharge in sloping aquifers using (1) conservative nonvolatile tracers of both atmospheric origin (e.g., chloride ions) and those originating from the topsoil (e.g., bicarbonate), (2) stable isotopes of water (e.g., ^{18}O and ^2H), and (3) environmental radioactive tracers (e.g. tritium ^3H). Such analytical methods provide essential estimations of recharge in mountainous regions that are otherwise difficult to obtain.

Professor Custodio worked repeatedly on the estimation of recharge in arid areas, especially in the Antofagasta Altiplano (Fig. 4), where he collaborated on different topics associated with the study of recharge estimation. He also developed many studies in the Atacama Desert of Chile, where he worked during the last 25 years of his career.

Professor Custodio was also interested in estimating paleo-recharge rates. He assumed the existence of previous wetter-than-present periods for the Atacama Desert,



Fig. 4 Professor Emilio Custodio surveying the saline soils of the Central Depression in the Antofagasta Region (Chile). Photo taken by Christian Herrera Lameli in 2015

and used environmental tracers, such as chloride ions and radiocarbon, to test this hypothesis. He demonstrated that tracer concentration and estimated water age are not directly linked to the time that recharge occurred, which is crucial for avoiding confusion when interpreting groundwater tracers and temporal paleo-recharge sequences from a causal perspective. His research into hyperarid areas such as the Pampa del Tamarugal and the Cordillera de la Costa, where a significant ^{14}C dating campaign was conducted to better understand the history of groundwater recharge since the end of the Pleistocene, was particularly noteworthy. His latest work with lithium and boron isotopes allowed for the age approximation of older waters of marine origin.

Professor Custodio integrated all methods of estimating groundwater recharge using environmental tracers, with emphasis on stable isotopes of the water molecule (Custodio 2019) in a volume of more than 1200 pages. This is undoubtedly another of his outstanding contribution to knowledge aimed at providing useful tools that contribute to the training of future hydrogeologists.

Volcanic aquifers

Professor Custodio started studying the hydrogeology of volcanic aquifers in the Canary Islands in the early 1970s when he was part of the project “Scientific Study of Water Resources in the Canary Islands—SPA.15, MOP-UNESCO 1975”. His interest in the Canaries was reflected in the development of several research projects, resulting in several doctoral theses and numerous publications. The projects addressed many different topics, from classical hydrogeology applied to volcanic aquifers to new approaches including economic and social aspects. Other volcanic islands such as Easter Island (Chile), were also studied. In this research,

a hydrogeochemical and isotopic study was conducted to make a connection between the knowledge achieved on the volcanic islands of the Canary Archipelago and the volcanic aquifer of Easter Island. In recent years, he focused on different volcanic settings in the Andean area.

Professor Custodio's knowledge of volcanic island hydrogeology was compiled in the HIRAVOL project, one of his latest works, where he shared his wide experience in this topic (Custodio 2020). He also left behind a team of hydrogeologists that will try to continue his legacy, not only in the Canaries, but also in several volcanic settings across the world.

Groundwater governance

Throughout Professor Custodio's extensive career and numerous publications and conferences, he consistently emphasized the imperative need for effective groundwater governance. He not only highlighted this critical necessity but also clearly defined the pivotal role of hydrogeologists in providing scientific knowledge to those responsible for governance.

Professor Custodio made significant contributions to establishing the scientific basis of groundwater overexploitation and the legislative criteria for declaring an aquifer as overexploited. These concepts were discussed at the Interregional Workshop on Groundwater Overexploitation, organized by the United Nations Department of Technical Cooperation for Development and held in the Canary Islands in 1991, an event he actively promoted.

This task also included making groundwater "visible", protecting it from contamination and unsustainable exploitation and taking the environment and other essential resources into account. Moreover, he advocated for the establishment of groundwater legislation that is not only more appropriate, effective, and realistic, but also has the aim of achieving sustainable management of groundwater. Professor Custodio emphasized the proactive preservation of aquifers, recognizing their significance in adapting to climate change and global transformation. He envisioned aquifers as an inheritance to be conserved for the benefit of both present and future generations. One of his last books (Custodio 2022) presented his vision of a holistic approach to sustainable groundwater management, essential for meeting present and future water demands while safeguarding environmental integrity and socioeconomic well-being.

He carried out work relevant to the implementation of the 'groundwater dimensions' of the European Council Water Framework Directive of 2000, and the foundation work for the Groundwater Protection 'Daughter' Directive of 2006, notably with a major contribution on the definition of 'baseline groundwater quality' (together with Professor W.M.

Edmunds). He was also very active in the follow-up of the actual implementation of both directives in Spain.

He worked together with another former IAH president, Stephen Foster (2004–2008), to assess whether regulatory agencies in Europe were able to cope with the threat to groundwater sustainability posed by intensive agriculture as well as the global threat to groundwater sustainability posed by illegal water wells.

Hydroethics

In reference to the ethics of groundwater management, Professor Custodio published several papers where he defended ethical thoughts that should be accounted for in the process of "making more freshwater available, which means more interference with the environment, altering the social context and depleting groundwater resources". Additionally, he addressed issues such as the "often highly inefficient use of freshwater, protecting groundwater reserves and preventing further degradation by contamination". Professor Custodio also demanded that there "are ethical issues to be seriously considered before creating a stressed environment and wasting badly needed economic and human resources, because solving this handicap involves not only science and technology, but also clear economics, social appreciation, and political will, all of them glued together by ethical behaviour".

For him, groundwater ethics dealt with present circumstances as well as with those of the future, represented by scenarios that, to be ethically acceptable, should be non-biased, scientifically feasible and free of preset orientation aimed at other objectives. Ethics play an important role in water policy-making, especially for groundwater. Science and technology contribute the means to convert objectives into assessments that help in decision-making at a higher level, which involves deep ethical and moral implications.

All this showed that Professor Custodio was concerned not only with high-level science, but also with the attitude a hydrogeologist must have in the handling of different issues that groundwater faces, as well as the identification of possible solutions.

Final remarks

Those of us who have been fortunate enough to work with Professor Custodio know that behind his serious image hid a coherent, consistent, and hard-working person, featuring selfless, austere, faithful qualities and good human values that were always evident. As a professional hydrogeologist or as a professor, he was always recognizable by his grave and even solemn way of speaking, whether he had a student or a general manager in front of him. He could also be defined by the enormous generosity he always showed

when sharing his knowledge, his availability to offer pertinent ideas to anyone who requested his help, and his willingness to teach, especially to the youngest students. These values, together with his privileged mind and unmatched work capacity, lead us to affirm that, undoubtedly, the hydrogeological science and profession would not have been the same without the emblematic figure of Professor Emilio Custodio.

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Declarations

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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