

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

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24 **Keywords:** Profile of eminent hydrogeologist, Spain, Latin America, Recharge, Volcanic
25 aquifers

26 Professor Emilio Custodio is honoured as a crucial figure in modern hydrogeology. His
27 extensive contributions to the field, both in academia and practical applications, have left an
28 indelible mark on water resource management globally. Through his pioneering research,
29 leadership roles, and dedication to education, Professor Custodio has been fundamental in
30 advancing the scientific understanding and ethical governance of groundwater resources. His
31 work continues to inspire and guide hydrogeologists around the world.**1. Biography**

32 Emilio Custodio was born in Barcelona, Spain, in 1939, the year that the Spanish Civil War
33 ended. He completed his primary school education in Solsona and attended secondary schools
34 in Granollers (Piarists) and Barcelona (Claretians). He pursued higher education at the *Escuela*
35 *de Ingenieros Industriales* (School of Industrial Engineering) at the old Polytechnic University
36 of Barcelona, where he graduated as the first in his class as an industrial engineer during the
37 “intensification” of chemistry in 1964. He later specialised in nuclear engineering, and gaining
38 his doctorate in 1972. In 1973, he started as associate professor at the *Universidad de*
39 *Tecnología Nuclear* (Nuclear Technology University) in Barcelona. He joined the *Universitat*
40 *Politécnica de Catalunya* (Polytechnic University of Catalonia), UPC, as an associate professor
41 in 1981, and became a full professor in 1986. He remained as an academic for his whole life,
42 continuing after his retirement in 2010 as an emeritus professor. Outside of academia, he
43 worked as an engineer from 1964-85, at the *Ministerio de Obras Públicas* (Ministry of Public
44 Works), in the *Dirección General de Obras Hidráulicas* (General Directorate of Hydraulic
45 Works) and in the *Comisaría de Aguas del Pirineo Oriental* (Eastern Pyrenees Water
46 Commissioner), later transformed into *Junta d’Aigües* (Water Board), and finally to *Agencia*
47 *Catalana del Agua* (Catalan Water Agency). Between 1997 and 2004, he was appointed as
48 director of the *Instituto Geológico y Minero de España (IGME*, Geological and Mining Institute
49 of Spain), an institution comparable with a national geological survey. During this period under
50 professor Custodio’s leadership, the IGME reformed into a research and development

51 institution, which gave it an international dimension. Professor Custodio was frequently invited
52 as an expert to numerous technical meetings organized by the United Nations educational,
53 scientific and cultural organisation (UNESCO), the international atomic energy agency (IAEA),
54 as well as other global organizations. Recognized for his leadership, he often chaired these
55 meetings. His active participation played a vital role in creating several key publications that
56 introduced new methods and strategies for evaluating and managing water resources. He was
57 also the founder, director, and teacher of the *Curso Internacional de Hidrología Subterránea*
58 (International Groundwater Hydrology Course), CIHS, a post-graduate university course
59 equivalent to a master's degree. The CIHS was the school of preference for many Spanish-
60 speaking hydrogeologists, and had a major impact on the development of the Ibero-American
61 hydrogeological community. Many current university professors, high-level government
62 managers and senior professionals in Spain, Portugal and Latin America are CIHS alumni.



63
64 **Fig. 1** Portrait of Professor Emilio Custodio in 2004 as General Director of the *Instituto*
65 *Geológico y Minero de España* (Geological and Mining Institute of Spain), painted by Juan
66 Ignacio Burguete Albalat. It is a tradition to make a painting of the outgoing director of the
67 institution, which is exhibited along with former directors.

68

69 **2. Relationship with the International Association of Hydrogeologists (IAH)**

70 Professor Custodio has always been highly committed to the International Association of
71 Hydrogeologists (IAH), since he first joined in 1974. In the periods 1980-1984, 1996-2000, and
72 2004-2009, he served as a member of the IAH board of directors, eventually becoming president
73 in 2000-2004. He made significant contributions to the scientific and organizational
74 development of the association and received the IAH presidents' award in 1998. He was
75 distinguished as an honorary member of the IAH in 2014 and of the IAH Spanish national
76 chapter (*Asociación Internacional de Hidrogeólogos – Grupo Español (AIH-GE)*) in 2016.

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

84 Earlier, he had chaired an IAH Spanish group (1980-1984) culminating in the creation of the
85 IAH Spanish chapter, of which he was president (1994-1998). In this period, Professor
86 Custodio's made an enormous effort in organizing and convening scientific meetings. It should
87 also be noted that Professor Custodio promoted the creation of an IAH national chapter in
88 Portugal.

89

90 **3. Awards and recognition**

91 Professor Custodio received numerous awards and distinctions throughout his prolific career,
92 for his outstanding scientific contributions to the field of hydrogeology, his dedication to

93 mentoring and education, and the personal attributes and values that made him a very dear
94 person.

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

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

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

116



117

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

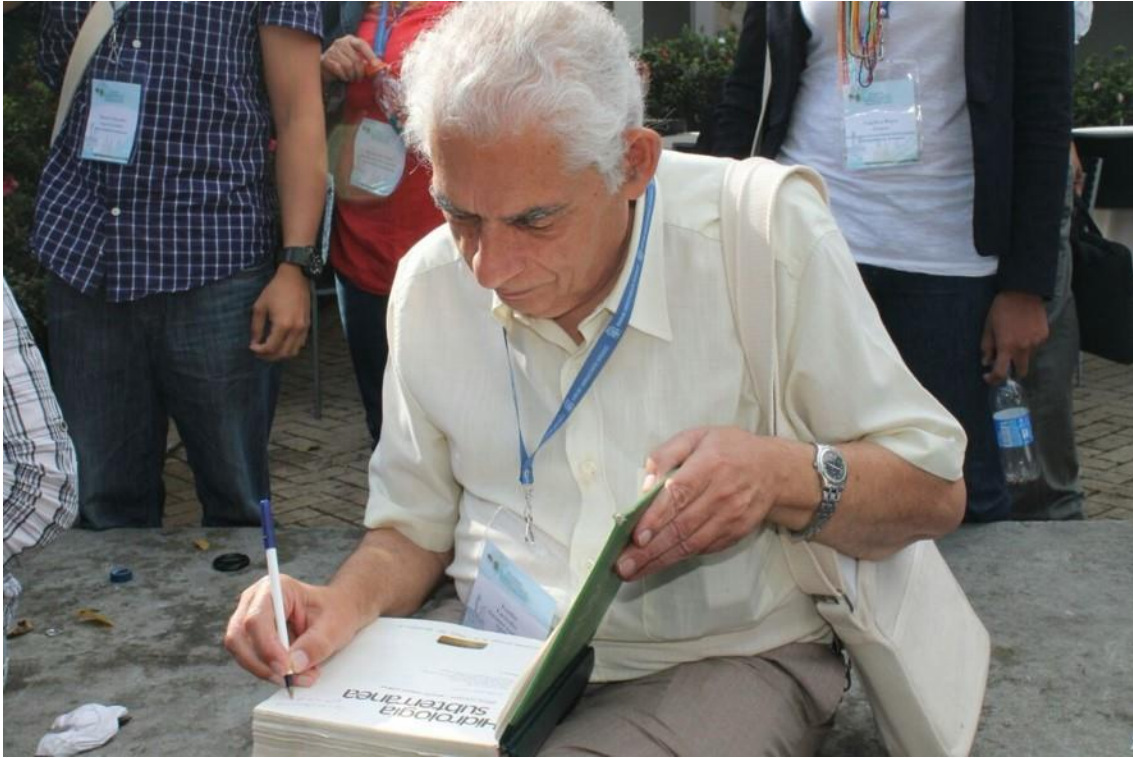
123 In 2011, AIH-GE organized an event in his honour and the book *Cuatro décadas de*
124 *investigación y formación en aguas subterráneas* (Four Decades of Research and Training in
125 Groundwater) was presented as a tribute. The book featured contributions from a wide range of
126 researchers and collaborators,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

128

129 **4. Academic legacy**

130 In 1967, jointly with Professor Llamas and under the umbrella of the International Hydrological
131 Decade of UNESCO (1965-74), Professor Custodio founded the CIHS in Barcelona (Spain),
132 which was endorsed by the UPC. The leadership comprised professionals from the *Ministerio de*

133 *Obras Públicas* (Ministry of Public Works) and *Aguas de Barcelona* (Barcelona Waters) and the
134 course quickly gained recognition as a global reference for hydrogeologists, especially in
135 Spanish-speaking countries.



136

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

141 In 1990, Professor Custodio initiated the official M.Sc. Program in Groundwater Hydrology at
142 UPC, and in 1991, he founded the private foundation *Centro Internacional de Hidrología*
143 *Subterránea* (International Center for Groundwater Hydrology (FCIHS)) in Barcelona, serving
144 as Director until 1997. From 1997 to 2004, he served as a member of the Foundation's Board of
145 Trustees. A total of 54 editions of the CIHS were conducted during 1967-2020, along with 20
146 editions (2003-2021) of the online version, two semi-presential editions in Argentina, and ten
147 editions (2012-2021) of the *Master Profesional de Hidrología Subterránea* (Master of
148 Groundwater Hydrology (MPHS)). All these programs took place at the UPC facilities. CIHS

149 trained over 1600 hydrogeologists, making it the longest-standing post-graduate course among
150 all Spanish universities. The CIHS became very successful, leading to an increased interest from
151 water professionals in Latin America to join this specialized course. This interest prompted the
152 creation of a shorter version of the one offered in Barcelona. The *Curso Hispanoamericano de*
153 *Hidrología Subterránea* (Latin American Groundwater course), a Latin American edition of the
154 course, has been taking place every two years in Montevideo, Uruguay, starting in 2000.
155 Professor Custodio lectured at all 54 editions of the CIHS and also at several editions of the
156 Latin American version.

157 After the closure of FCIHS, Professor Custodio actively collaborated in the preparation and
158 teaching the master's course in hydrogeology held at the University of Barcelona during the last
159 two years of this life.

160 One remarkable aspect of Professor Custodio's contribution to the field of hydrogeology is the
161 book *Hidrología Subterránea* (Groundwater Hydrology; Custodio and Llamas 1976), edited in
162 1976 and 1983, of which he was a co-editor along with Professor Llamas, as well as the author
163 of most of the chapters. This comprehensive textbook spanned over 2400 pages across two
164 volumes, created to help educate future hydrogeologists.

165 His prolific scientific work included over 700 publications (including more than 130 in
166 scientific and technical journals, and over 40 book chapters), and the supervision or co-
167 supervision of 27 doctoral theses, and 12 master's theses. He has authored or co-authored at
168 least 13 books and served as an editor or co-editor for 17 others.

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

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

184

185 **4.1 Hydrochemical and environmental isotope studies**

186 Professor Emilio Custodio is recognised as a leading geoscientist for the development and
187 application of hydrochemical and isotopic techniques in evaluating the physical and chemical
188 dynamics of a wide range of groundwater systems. He led the incorporation of hydrochemistry
189 and environmental isotopes as research tools in hydrogeological studies in the late 1960s when
190 he completed his Ph.D. on "Groundwater Dating: dating with radioisotopes, variation of
191 isotopic ratios and pure chemical characteristics: application to the Llobregat River Delta".
192 Since then, he proceeded to apply hydrochemical and isotopic techniques in the majority of his
193 works, promoting their use in both hydrogeological research and industry.

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

200 Other studies focused on the evaluation of particular hydrogeological processes. His work
201 related to coastal aquifers and groundwater recharge will be commented in two separate sections

202 below. Beyond the characterisation of physical hydrogeological systems, he applied
203 hydrogeochemical and isotopic tools to study groundwater pollution and decontamination. In
204 fact, his works contributed to the understanding of the impact of atmospheric deposition to
205 groundwater salinity.

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

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

215 **4.2 Coastal aquifers**

216 Professor Custodio contributed extensively to the scientific understanding and practical
217 management of coastal aquifer systems, both in natural and perturbed conditions across diverse
218 settings and contexts. His studies on this topic started in the late 1960s for the aquifers of the
219 Delta del Llobregat (Spain). An initial article dates to 1970, focusing on marine intrusion in this
220 area. Throughout his career, he authored numerous works in the form of articles in scientific
221 journals, conference proceedings (Salt Water Intrusion Meeting (SWIM), IAH, International
222 Symposium on Managed Aquifer Recharge (ISMAR), etc.), studies, reports, and books. He led
223 various projects in the Mediterranean; various islands, predominantly in volcanic settings such
224 as the Canaries, Easter Island (Chile), Doñana area, and also worked in Europe, and Latin
225 America. In more recent times, his research extended to the study of the saline interface in
226 Andean Salt Flats.

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

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

235

236 **4.3 Recharge studies**

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

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

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

253 Professor Custodio was also interested in estimating paleo-recharge rates. He assumed the
254 existence of previous wetter-than-present periods for the Atacama Desert, and used
255 environmental tracers, such as chloride ions and radiocarbon to test this hypothesis. He
256 demonstrated that tracer concentration and estimated water age are not directly linked to the
257 time that recharge occurred. This is crucial to avoid confusion when interpreting groundwater
258 tracers and temporal paleo-recharge sequences from a causal perspective. His research into
259 hyperarid areas such as the Pampa del Tamarugal and the Cordillera de la Costa was of
260 particularly noteworthy, where a significant ^{14}C dating campaign was conducted to better
261 understand the history of groundwater recharge since the end of the Pleistocene. His latest work
262 with lithium and boron isotopes allowed for the age approximation for older waters of marine
263 origin.

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



269

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

272 **4.4 Volcanic aquifers**

273 Professor Custodio started studying the hydrogeology of volcanic aquifers in the Canary Islands
274 in the early 1970s when he was part of the project “Scientific Study of Water Resources in the
275 Canary Islands - SPA.15” (MOP-UNESCO 1975). His interest in the Canaries was reflected in
276 the development of several research projects, with the result of several doctoral theses and
277 numerous publications. The projects addressed many different topics, from classical
278 hydrogeology applied to volcanic aquifers to new approaches including economic and social
279 aspects. Other volcanic islands, such as Easter Island (Chile), were also studied. In this research,
280 a hydrogeochemical and isotopic study was conducted to make a connection between the
281 knowledge achieved on the volcanic islands of the Canary Archipelago and the volcanic aquifer
282 of Easter Island. In recent years, he focused on different volcanic settings in the Andean area.

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

287

288 **4.5 Groundwater governance**

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

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

298 This task also included making groundwater "visible", protecting it from contamination and
299 unsustainable exploitation, taking the environment and with other essential resources into
300 account. Moreover, he advocated for the establishment of groundwater legislation that is not
301 only more appropriate, effective, and realistic, with the aim of achieving sustainable
302 management of groundwater. Professor Custodio emphasized the proactive preservation of
303 aquifers, recognizing their significance in adapting to climate change and global transformation.
304 He envisioned aquifers as an inheritance, to be conserved for the benefit of both present and
305 future generations.

306 One of his last books (Custodio et al. 2022) presented his vision of a holistic approach to
307 sustainable groundwater management, essential for meeting present and future water demands
308 whilst safeguarding environmental integrity and socioeconomic wellbeing.

309 He carried out work relevant to the implementation of the ‘groundwater dimensions’ of the
310 European Council Water Framework Directive of 2000, and the foundation work for the
311 Groundwater Protection ‘Daughter’ Directive of 2006, notably with a major contribution on the
312 definition of ‘baseline groundwater quality’ (together with Professor W.M. Edmunds). He was
313 also very active on the follow up of the actual implementation of both directives in Spain.

314 He worked together with another former IAHR president, Stephen Foster (2004-08) to assess
315 whether regulatory agencies in Europe were able to cope with the threat to groundwater
316 sustainability posed by intensive agriculture and also the global threat to groundwater
317 sustainability posed by illegal water wells.

318

319 **4.6 Hydroethics**

320 In relation with the ethics of groundwater management, Professor Custodio published several
321 papers where he defended ethical thoughts that should be accounted in the process of “making
322 more freshwater available, which means more interference with the environment, altering the
323 social context and depleting groundwater resources”. He also claimed the “often highly
324 inefficient use of freshwater, protecting groundwater reserves and preventing further
325 degradation by contamination”. Professor Custodio also demanded that there “are ethical issues
326 to be seriously considered before creating a stressed environment and wasting badly needed
327 economical and human resources, because solving this handicap involves not only science and
328 technology, but also clear economics, social appreciation, and political will, all of them glued by
329 ethical behaviour”.

330 For him, groundwater ethics dealt with present circumstances, as well as with those of the
331 future, represented by scenarios that to be ethically acceptable should be non-biased,
332 scientifically feasible and free of pre-set orientation aimed at other objectives. Ethics play an
333 important role in water policy-making, especially for groundwater. Science and technology

334 contribute with the means to convert objectives into assessments that help in decision making at
335 a higher level, which involves deep ethical and moral implications.

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

339

340 **5. Final remarks**

341 Those of us who have been fortunate enough to work with Professor Custodio know that,
342 behind a serious image he hid a coherent, consistent, and hard-working person, featuring
343 selfless, austere, faithful qualities and human good values. As a professional hydrogeologist or
344 as a professor, he has always been recognizable by his grave and even solemn way of speaking,
345 whether he had a student or a general manager in front of him. He can be defined also by the
346 enormous generosity he always showed when sharing his knowledge, his availability to help
347 with pertinent ideas to anyone who requested it, and his willingness to teach, especially to the
348 youngest students. These values, together with his privileged mind and unmatched work
349 capacity, lead us to affirm that, undoubtedly, the hydrogeological science and profession would
350 not have been the same without the emblematic figure of Professor Emilio Custodio.

351 **ACKNOWLEDGEMENT**

352

353 The co-authors want to give special thanks to Professor Jaime Gómez Hernández, from the
354 Technical University of Valencia (Spain) and the editors, for their final reviews of the paper and
355 to Luis Araguás and Javier Custodio for their contribution to complete biographical details.

356

357 **CONFLICT OF INTEREST**

358

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

360

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