

We Lose Ground: Global Assessment of Land Subsidence Impact Extent

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Abstract: Depletion of groundwater aquifers along with all of the associated quality and quantity problems which affect profitability of direct agricultural and urban users and linked groundwater-ecosystems have been recognized globally. During recent years, attention has been devoted to land subsidence—the loss of land elevation that occurs in areas with certain geological characteristics associated with aquifer exploitation. Despite the large socioeconomic impacts of land subsidence most of these effects are still not well analyzed and not properly recognized and quantified globally. In this paper we developed a land subsidence extent index (LSIE) that is based on 10 land subsidence attributes, and applied it to 113 sites located around the world with reported land subsidence effects. We used statistical means to map physical, human, and policy variables to the regions affected by land subsidence and quantified their impact on the index. Our main findings suggest that LSIE increases between 0.01 and 5% by changes in natural processes, regulatory policy interventions, and groundwater usage while holding all other variables unchanged. Effectiveness of regulatory policy interventions vary depending on the lithology of the aquifer system, in particular its stiffness. Our findings suggest also that developing countries are more prone to land subsidence due to lower performance of their water governance and institutions.

Keywords: aquifer overdraft; water scarcity; groundwater pumping regulations; impacts; policy effectiveness; land subsidence extent index

JEL Classification: Q25, Q56.

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We Lose Ground:

Global Assessment of Land Subsidence Extent and its Causes

Abstract: Depletion of groundwater aquifers along with all of the associated quality and quantity problems which affect profitability of direct agricultural and urban users and linked groundwater-ecosystems have been recognized globally. During recent years, attention has been devoted to land subsidence—the loss of land elevation that occurs in areas with certain geological characteristics associated with aquifer exploitation. Despite the large socioeconomic impacts of land subsidence most of these effects are still not well analyzed and not properly recognized and quantified globally. In this paper we developed a land subsidence extent index (LSIE) that is based on 10 land subsidence attributes, and applied it to 113 sites located around the world with reported land subsidence effects. We used statistical means to map physical, human, and policy variables to the regions affected by land subsidence and quantified their impact on the index. Our main findings suggest that LSIE increases between 0.01 and 5% by changes in natural processes, regulatory policy interventions, and groundwater usage while holding all other variables unchanged. Effectiveness of regulatory policy interventions vary depending on the lithology of the aquifer system, in particular its stiffness. Our findings suggest also that developing countries are more prone to land subsidence due to lower performance of their water governance and institutions.

1. Introduction

Land subsidence (LS), defined as the settlement of the land surface, is generated by human-induced and natural-driven processes, including natural compaction of unconsolidated deposits (Zoccarato et al., 2018), and human activities such as subsurface water mining, or extraction of oil and gas (Gambolati et al., 2005). LS is a global problem (Galloway et al., 2016; Herrera-Garcia et al., 2021; Kok and Costa, 2021), mostly studied and recognized, to different extents, in association with aquifer overexploitation (which is the focus of this paper). LS occurrence around the world is most prominent in those aquifer systems composed of loose unconsolidated materials (e.g., sands, clays, and silts) that are over-pumped (e.g., Poland, 1984; Tomás et al., 2005; Gambolati and Teatini, 2015; Bonì et al., 2015).

63 Climate change impacts on water availability and population growth are expected to
64 increase competition for water, leading to extensive groundwater withdrawals. The expected
65 overexploitation of aquifers will exacerbate current and future damage from various LS impacts.
66 LS causes significant damages to local communities and to the environment (Yoo and Perrings,
67 2017; Teatini et al., 2018). As such, identifying the types of damages and quantifying them in
68 terms of the various physical impacts and their short- and long-term economic costs would be an
69 essential first step for preparing policies to address this problem. However, most studies on LS are
70 indicative in the sense that they identify the driving processes and measure the physical effects of
71 LS in specific localities. Few are the works that assess the global impacts of LS in terms of social,
72 environmental, and/or economic consequences.

73 A review of existing literature suggests that LS can cause the following impacts (e.g.,
74 Poland, 1984; Holzer and Galloway, 2005; Lixin et al., 2010; Bru et al., 2013; Erkens et al., 2016),
75 as summarized in Dinar et al. (2020): (1) Socio-economic impacts, such as structural damages (Bru
76 et al., 2013); (2) Environmental damages, such as malfunctioning of drainage systems (Viets et al.,
77 1979); (3) Geological-related damages that affect underground lateral water flows (Poland, 1984);
78 (4) Environmental damages, such as reduced performance of hydrological systems (Poland, 1984);
79 (5) Environmental damages, such as wider expansion of flooded areas (Poland, 1984); (6)
80 Hydrogeological damages that result in groundwater storage loss (Holzer and Galloway, 2005;
81 Béjar et al. 2017); (7) Impact on adaptation ability to climate change (such as the loss of the buffer
82 value of groundwater in years of scarcity) Erkens et al., 2016; (8) Groundwater contamination,
83 such as seawater intrusion resulting in decrease of farmland productivity in coastal aquifer systems
84 and decrease of fresh-water availability (Holzer and Galloway, 2005; Poland, 1984); (9) Loss of
85 high-value transitional areas (e.g., saltmarshes) (Viets et al, 1979); and (10) Shift of land use to
86 poorer activities (e.g., from urbanized zones to rice fields, from rice fields to fish and shellfish
87 farms, from fish farms to wastewater ponds) (Heri et al., 2018). A summary of the literature used
88 for the ten LS attributes and their impacts is summarized in Appendix A (Table A1).

89 Estimates of economic damages from land subsidence are not yet widely available, and
90 most of the published studies on this phenomenon focus on a physical quantification of subsidence
91 and on cataloguing the damages (Borchers and Carpenter, 2014). Few works have assessed local
92 LS damages (e.g., Jones and Larson, 1975; Warren et al., 1975; Lixin et al., 2010; Tomás et al.,
93 2012; Sanabria et al., 2014; Yoo and Perrings, 2017; Wade et al., 2018; and Díaz et al., 2018).

94 Selected damages cited in the literature range from \$756 million in the Santa Clara Valley of
95 California (Borchers and Carpenter, 2014), to \$1.3 billion in the San Joaquin Valley of California
96 between 1955 and 1972, in 2013 dollars, to \$18.03 billion in the Tianjin metropolitan area in the
97 period up to 2007 (Lixin et al., 2010). It is worth noting that, since the studies leading to these
98 estimates use different approaches, refer to different sizes of affected regions, and span over
99 different periods of time, one should not attempt to compare the values but rather use them as
100 indicative only. A recent study (Kok and Costa, 2021) enumerates the various types of costs
101 associated with LS and suggests a standardize economic framework for their cost evaluation.

102 In a recent publication, Herrera-Garcia et al. (2021) identified 200 locations (mostly urban)
103 in 34 countries that experienced LS during the past century. However, these authors also indicate
104 that the LS extent is known only in one third of these locations. Given lack of direct data on
105 damages, Herrera-Garcia et al. (2021) use what they define as the exposure to potential land
106 subsidence (PLS) and focus on areas where the probability for potential subsidence is high. Their
107 calculations suggest that PLS affects 8 percent of the global land surface, and that 2.2 million
108 square kilometers of global land is exposed to high to very high probability for PLS, affecting 1.2
109 billion urban inhabitants and threatening nearly US\$ 8.2 trillion GDP. This estimate on the global
110 economic exposure could be a lower-level estimate because the authors assumed that the GDP per
111 capita is homogenous within each country, not taking into account the geographical variations in
112 productivity, for example between different regions within a country, or between cities and rural
113 areas. However, this economic estimate on the global subsidence exposure does not directly
114 translate to subsidence impact or damages. The lack of information on the cost of damages caused
115 by current and historical subsidence worldwide, prevents these authors from evaluating the impact
116 of global land subsidence.

117 Realizing the need for a global assessment of LS impacts and the present difficulty to
118 provide global economic quantification for those effects (Kok and Costa (2021), Herrera-Garcia
119 et al. (2021)), this paper has taken an approach of quantitatively (not economically) assessing
120 global LS impact extents and their determinants. We start with a meta-analysis and review of
121 relevant literature on LS occurrence and physical quantification of its impacts in various sites
122 around the world. In the absence of economic value for the LS-induced damage, we develop an
123 index to assess the LS impact extent (LSIE), using the classification of the 10 LS impacts listed
124 above. This assessment allows us to identify different types of impacts in different locations and

125 is used to explain the effects of physical, regulatory, and population conditions on LSIE. Such
126 conditions include aquifer lithology, managing institutions, social systems, existing policies,
127 population pressure, water-level depletion from over-pumping, and several others.

128 From here on the paper develops as follows: Section 2 explains the principles used to
129 develop the LSIE index. We then present in Section 3 an empirical investigation into the social,
130 physical and institutional determinants most likely affecting land subsidence and its impact as
131 measured by LSIE. Section 4 presents the data-collection process, the variables constructed, and
132 the hypotheses regarding their effects on LSIE. This is followed in Section 5 by the empirical
133 specifications of our models and the derived hypotheses. Section 6 includes results from the LSIE
134 global distribution, and results from the statistical analysis. The results are followed by policy
135 simulations in Section 6, with estimates of the marginal impact of policy variables on the extent
136 of the LSIE. Discussion on the policy results is provided in Section 7. In Section 8 we present our
137 conclusions and policy implications.

138

139 **2. The LS Impact Extent (LSIE) Index**

140 Use of indicative indexes to assess environmental health status has been practiced by many
141 national and international agencies (OECD, 2003; EEA—Gabrielsen and Bosch, 2003; EPA—
142 Fiksel et al, 2012). Use of indexes allows comparison across states and geographical regions
143 (OECD, 2003). As explained below, we developed an indicative index to measure LS impact
144 extent in the locations of the dataset we compiled.

145 Due to the heterogeneous and partial nature of the information we extracted from all
146 reviewed LS studies, and following the earlier discussion on the difficulties in comparing the
147 extent of impacts within an LS site and across LS sites, we adopted and adapted the Qualitative
148 Structural Approach for Ranking (QUASAR) method, as explained in Galassi and Levarlet (2017).
149 QUASAR allows to compile the various impacts of LS identified in a given location into one index.
150 A review of approaches to assess non-continuous impacts of human intervention on the
151 environment can be found in Purvis and Dinar (2020). We follow Purvis and Dinar (2020), who
152 apply a similar scoring method to indicate various effects of inter- and intra-basin water transfers
153 on basin welfare.

154 Our assessment model was developed as follows: We conducted an exhaustive review (details are
155 provided below) of related literature that indicate different types of land subsidence impacts.

156 During the review of the literature we identified impacts that were discussed by the authors of the
 157 publications. Each LS reviewed was associated with up to N impacts (we identified $N=10$ in the
 158 papers reviewed). We identified several publications referring to the same LS site. Some of them
 159 included subsets of the N LS attributes. For example, if we had 2 sources for the same location
 160 with LS issues and one source reported the existence of LS attributes 3, 5, 6 and the second source
 161 for the same location reported the existence of LS attributes 2, and 4, then we assigned this location
 162 as having LS attributes 2, 3, 4, 5, 6. Therefore, in these cases we combined the LS attributes from
 163 the various reports. Because no quantitative measurement was provided, we just marked whether
 164 or not an impact is mentioned in a publication with a value of 0 or 1 (No/Yes). Let S be the set of
 165 sites with LS impacts that we identified, and let A_{si} be LS impact i , $i = 1, \dots, N$ in site s , $s=1, \dots,$
 166 S .

167
 168 Then:

$$170 \quad A_{si} = \begin{cases} 0 & \text{if LS impact } i \text{ has no effect on site } s \\ 1 & \text{if LS impact } i \text{ has any effect on site } s \end{cases} \quad \forall i = 1, \dots, N; s = 1, \dots, S \quad [1]$$

171
 172 Then the total net effect (NE) of LS (the composite impact) in a given site s is the sum of
 173 the number of LSIE attributes that affect a given site:

$$174 \quad NE_s = \sum_{i=1}^N A_{si}, \quad [2]$$

175
 176 with NE being an integer. Given the nature of the A_{si} 's we can expect that $0 < NE_s \leq N$. Then
 177 the $LSIE$ is defined as:

$$178 \quad LSEI_s = NE_s / N, \text{ where } 0 < LSEI_s \leq 1. \quad [3]$$

179
 180 It is assumed that the more LS impact types (coined later in the paper as 'attributes') are
 181 identified in a site, the larger the overall impact of LS. It should be mentioned that the lack of
 182 detailed information of the impact of LS of different study cases can lead to a bias in the evaluation
 183 of the index. That is, for some sites recorded in the database, the available information about land
 184 subsidence and its effects is very limited and this fact can introduce deviations in our calculations
 185 of the index. Another caveat of the $LSIE$ is that a subsidence event could occur with only one type

186 of impact, but severe, and would be seen as less important. For example, the case of Iran or Mexico,
187 where subsidence occurs inland and flooding effects are unlikely, but the intensity of the other
188 impacts is very harmful. In that respect LSIE does not provide a good quantification of the LS
189 impact, but rather a measure of its extent. To address some of these caveats we introduced weights
190 to the LSIE attributes, in an attempt to more appropriately reflect differences in the relative effects
191 of these attributes.

192

193 **3. Land Subsidence Extent and its Causes**

194 LS occurs due to a combination of social, policy, and physical factors—stratigraphic, lithological
195 and geomechanical characteristics of the aquifer system, and groundwater table depletion, or
196 lowering of the piezometric head for a phreatic or confined aquifer system, respectively (Poland,
197 1984; Tomás et al., 2011; Gambolati and Teatini, 2015). This latter variable is controlled by the
198 anthropogenic pressure on the aquifer system, usually represented by urban and agricultural
199 demands, and is strictly related to the rate of groundwater pumping and policies to regulate water
200 pumping (Poland et al., 1984; Freeze, 2000; Zhou et al., 2019). For the sake of completeness of
201 reporting about the survey and analysis of literature LS impacts, definitions, impact evaluation,
202 proxy variables, and results, we refer the readers to Appendix A Table A1.

203 We follow (See Appendix Table A1) the suggested list of causes identified in the various
204 publications cited above, referring mainly to water availability, human pressure, aquifer lithology
205 characteristics, governance and regulations (see also Kok and Costa 2021; Herrera et al. 2021).
206 The general relationship that we estimate can be described by the following general equation:

$$207 \text{LSIE} = f(\text{Scr}, \text{Pop}, \text{Irr}, \text{Suw}, \text{Lit}, \text{Dep}, \text{Reg}, \text{Dev}) \quad [4]$$

208 where *Scr* indicates existence of water scarcity in the region that depends on the aquifer system.
209 Scarcity leads to higher dependency on the aquifer system, making it more prone to LSIE. *Pop* is
210 a measure for population growth rate in the region that depends on the aquifer system during the
211 years over which the land has subsided, indicating the pressure for water supply on the aquifer
212 system. Higher values of *Pop* mean a larger level of pressure on the aquifer system and thus, higher
213 level of LSIE; *Irr* is a measure of whether or not irrigation occurs in the vicinity of the aquifer
214 system that potentially can be overexploited and impact the LSIE; *Suw* measures availability of
215 surface water in the region, suggesting a reciprocal impact of *Suw* on LSIE; *Lit* is a measure of the
216 lithology of the aquifer system, indicating its stiffness. Aquifer systems that are loose will be more

217 prone to LSIE; *Dep* is a measure of the groundwater level depletion during the years in which the
218 aquifer system has subsided. A higher level of *Dep* is expected to lead to a higher value of LSIE;
219 *Reg* is a measure of existence and effectiveness of groundwater pumping regulatory measures. A
220 higher value of *Reg* is expected to lead to a lower level of LSIE. Finally, we introduce a variable
221 (*Dev*) that indicates whether or not the aquifer system is located in a developing or a developed
222 country, expecting that due to a more advanced governance in a developed country the associated
223 LSIE level will be lower. An analysis of possible multicollinearity among these independent
224 variables suggests that they are not correlated and, thus, multicollinearity is not a problem.

225 In summary, the model incorporates three types of causes: characteristics of the aquifer
226 hydrogeological setting (*Lit*), regulatory intervention and governances (*Reg*, *Dev*), and pressure on
227 the aquifer system (*Scr*, *Pop*, *Irr*, *Suw*, *Dep*). Each of these is expected to affect the extent of land
228 subsidence in a different direction, as is analyzed below (See Appendix Table A1, column 1 and
229 4).

230

231 **4. Study Area, Data, Variable Construction, and General Hypotheses**

232 Technical published articles were retrieved, using search engines and publication databases, such
233 as Jstore (www.jstor.org) and Agricola ([https://www.ebsco.com/products/research-](https://www.ebsco.com/products/research-databases/agricola)
234 [databases/agricola](https://www.ebsco.com/products/research-databases/agricola)). We focused on technical papers in peer-reviewed journals and on books and
235 book chapters. We searched only for English-written documents. We used the following
236 keywords—land subsidence, groundwater, over-pumping, economic analysis, hydrology, land
237 subsidence impacts—to search for titles, abstract contents, and keyword lists of the publications.
238 The search team included one graduate student and two upper-level undergraduate students
239 (serving as data analysts) overseen by the lead author of this paper over the period January 2019-
240 June 2020.

241 A set of 183 papers was identified and read, separately, by the data analysts and were
242 discussed for consistency and accuracy of the coding. Of the papers read, 45 were dismissed either
243 because the information on land subsidence impact was not included, or because they focused on
244 methods to model land subsidence. A total of 38 papers referred to same locations. For each
245 location, information in the various papers related to that location was examined and consolidated.
246 By the end of the data collection phase, we ended up with 119 different sites. Each site is
247 characterized by a set of the variables, including coordinates of location of the aquifer system, to

248 be used for collection of additional data that is geographically related. The variables that were
249 collected or constructed are presented below with an explanation on how they were constructed.
250 The 119 sites with identified LS span over 32 countries across the globe (Figure 1).

251 A recent publication (Herrera-Garcia et al. (2021)) identified 200 land subsidence locations
252 around the world. Our search yielded 119 (119/200=59%) locations, but due to data deficiencies,
253 we ended up with 113 (113/200=56%) locations in our operational dataset. Given the objective of
254 devising the LSIE, the number of observations in our study is sufficient. Since we used published
255 papers in peer reviewed journals we have considered their content as highly reliable.

256 LSIE was calculated as described in equation [3]. A given location facing LS effects could
257 have between 1 and 10 types of LS impacts, thus, LSIE ranges between 0.1 and 1.0. The higher
258 the LSIE value the more extreme is the LS effect in that site. LSIE is calculated using two
259 assumptions: LSIE-EW assumes an equal weight for each of the ten attributes. We also developed
260 a weighted version of LSIE (LSIE-W), employing a Delphi technique for obtaining a vector of
261 weights assigned to each of the ten attributes. For a detailed description of the Delphi technique
262 and the procedure we employed to obtain the weights of the ten attributes see Appendix B. LSIE-
263 EW and LSIE-W are used as the dependent variable in the statistical analyses presented in the next
264 section.

265 While the objectives of the various papers we surveyed and the methods they use differ,
266 the information in the different papers surveyed by us provide also background information
267 independent of the objective of the particular paper and the methods used. This allowed us to
268 assign the binary (0/1) values to the different attributes we identified across the different studies.
269 Because we measure the (existence of the) attributes as yes/no, we minimize the level of bias due
270 to use of different measurement approaches and techniques. Indeed, this could be at the expense
271 of assigning different groups of attributes the same score, even though, they might have different
272 impacts.

273

274 *4.1 Impact of explanatory variables on LSIE*

275 The discussion below sets the direction of impacts of each of the explanatory variables on LSIE
276 (directions of impacts are the same in the case of LSIE-EW and LSIE-W), ceteris paribus. Our
277 hypotheses regarding the directions of impact between the explanatory variables and the LSIE are
278 based on previous evidence found in the literature summarized in Appendix A (Table A1).

279 *Scr*, indicating water scarcity in the region that depends on the aquifer system, is a
280 dichotomous variable (0/1) with a value of 1 if the region was mentioned as subject to drought,
281 with no alternate water resources from groundwater or surface water (that can ease the pressure
282 from the aquifer on site), or just a direct statement of water scarcity. A value of 0 would be assigned
283 otherwise. Facing scarcity would imply a higher value of LSIE.

284 *Pop*, the population pressure on the water resources in the region, is measured by annual
285 population growth and estimated as the slope of the linear regression equation of the three-year
286 population observations of that location, spanning between 1995 and 2015 (or the nearest census
287 years in the study area) as an indication for population growth trends. Note that this variable is
288 drawn from either the jurisdiction where the study area is located at or nearest the provincial level
289 jurisdiction if the area of study spans more than a single city. Positive values indicate an increase
290 in population and negative values indicate population decrease. We assume that the effect of the
291 *Pop* variable is quadratic. That is, as population grows, pressure on the aquifer water increases,
292 but that effect is reduced due to population self-realization of water scarcity, and behavioral
293 adjustment, after a certain level of consumption (Singh, 2018). Mathematically we expect $\frac{\partial LSIE}{\partial Pop} \geq$
294 0 ; $\frac{\partial^2 LSIE}{\partial Pop^2} \leq 0$.

295 *Irr* indicates whether irrigated lands are identified in or around the subsiding area,
296 suggesting higher possible pressure on the aquifer system. This would imply that groundwater has
297 been used for agricultural purposes. *Irr* is a binary variable (0/1) where 0 indicates that there is no
298 evidence of groundwater use for irrigation, and 1 indicates otherwise. Having irrigated land in the
299 region would imply a higher value of LSIE.

300 *Suw* indicates whether the area currently has access to alternative water sources (surface
301 water such as lakes, rivers or reservoirs). It is a binary variable (0/1) where 0 indicates no evidences
302 of alternative water source at surface level, and 1 otherwise. The determination of surface water
303 availability was based on two methods: (1) whether existing research identifies the use of such
304 water source in the area of study; and (2) if a major surface waterbody is located within the
305 geographical boundary of the study area. Having access to alternative water sources would imply
306 a lower level of LSIE.

307 *Lit* is a ranking variable associated with the lithology of the aquifer system, based on data
308 in the global map by Hartmann and Moosdorf (2012). We ranked the identified lithologies of the

309 aquifers based on their impact on land subsidence. Sediment-based lithologies are more prone to
 310 land subsidence than rock-based lithologies, and between sediments the unconsolidated ones are
 311 the most susceptible to face LS. Table 1 presents a classification of the main lithologies generally
 312 composing aquifer systems in relation to LS propensity. Class 1 encompasses unconsolidated
 313 sediments made by mixtures of sand, silt, and clays together with pyroclasts. Their stiffness is
 314 generally low and, consequently, Class 1 aquifer systems are very prone to subsidence. Class 2
 315 includes the rocks “derived” from those sediments (e.g., mainly sandstones and conglomerates)
 316 with a lesser subsidence propensity. Aquifer systems belonging to Class 3 are all other kind of
 317 rocks with extremely low subsidence propensity. The lithology variable, *Lit*, captures what the LS
 318 literature suggests to be the lithological control of land subsidence (Notti et al., 2016). A higher
 319 lithology class —i.e. a stiffer soil—is associated with a lower level of LS.

320

321 <Table 1 About Here>

322 Table 1: Lithology class ranking for land subsidence propensity resulting from groundwater
 323 pumping.

Lithology class	LS Propensity Ranking
1. sedimentary unconsolidated	1
2. sedimentary siliciclastic	2
3. carbonates	3
4. sedimentary mixed	2
5. plutonic acid	3
6. volcanic acid	3
7. metamorphic	3
8. pyroclasts	1
9. volcanic intermediate	3

324 Source: Authors elaboration based on map in Hartmann and Moosdorf (2012).

325 Note: Propensity to LS declines as values increase from 1 to 3.

326

327

328 *Dep* represents the groundwater depletion during a given period (loss in water table levels)
 329 and is based on data generated by the WaterGAP model (Döll et al., 2014). The generated data

330 provide year-to-year change of groundwater levels between 1960 and 2010 for each aquifer system
331 in our dataset. Negative values represent depletion and positive ones are rise of groundwater levels.
332 Based on this dataset, we created two depletion variables: (1) $Dep_1 = GW_Depletion_1960-2010$
333 which is the net depletion during 1960-2010, measured as the difference between the GW level in
334 2010 and in 1960; (2) $Dep_2 = Trend_GW_Depletion$ which is the slope of the regression line going
335 through the set of five decadal GW depletion data points.¹ Decadal GW Depletion 2000-2010, for
336 example, is the loss in GW level between 2000 and 2010. It is assumed that Dep_1 or Dep_2 are
337 affecting LSIE such that the larger is Dep_j , $j=1, 2$, the larger is the effect on LSIE, and that this
338 effect increases at an increasing rate as Dep_j , $j=1, 2$, grows beyond a given level (because higher
339 values of Dep_j , $j=1, 2$, introduce new dimensions/attributes of LSIE). Mathematically we expect
340 that $\frac{\partial LSIE}{\partial Dep_j} > 0$, and $\frac{\partial^2 LSIE}{\partial Dep_j^2} > 0$ for $j=1,2$.

341 *Reg* is an ordinal (ranking) variable measuring whether each site has established adequate
342 control measures on groundwater extraction. A value of 1 indicates that the site has no legislations
343 or regulations to controll groundwater use and has no enforcement efforts in place. A value of 2
344 was assigned if some regulatory efforts are in place but are not enforced or have suffered through
345 prolonged mismanagement of its groundwater resources. A value of 3 was assigned to the site if
346 evidence suggests a history of regulatory efforts are in place and such regulations have been
347 adequately managed. The more effective the regulations and enforcement, the lower is LSIE.

348 *Dev* indicates whether the country in which the aquifer with LS impact is a developing
349 country (=1) or a developed country (=0). Developed countries with improved level of governance
350 may face lesser problems of water mismanagement (Saleth and Dinar, 2004), and thus, a developed
351 country is expected to face a lower level of LSIE.

352 We also introduced two interaction terms in our model. The interaction variable $Irr \times Suw$
353 allows to determine whether or not the effect of nearby irrigated land in the site depends on whether
354 the site has access to alternative water sources. In the same way we introduced the interaction
355 variable $Reg \times Dev$ to determine whether or not a site with higher level of regulation of GW
356 extraction depends on whether or not the country to which it belongs is a developed or a developing
357 country.

¹ Decadal GW Depletion 2000-2010, Decadal GW Depletion 1990-2000, Decadal GW Depletion 1980-1990, Decadal
GW Depletion 1970-1980, and Decadal GW Depletion 1960-1970.

358

359 **5. Empirical Specifications and Hypotheses**

360 The model in [4] is developed using linear terms for all variables and quadratic relationships for
361 *Pop* and *Dep*. Given that our dependent variable, LSIE, contains real values that range from 0.1 to
362 1.0 and between 0.028 and 0.960 for LSIE-EW and LSIE-W, respectively, we use the ordinary
363 least squares (OLS) estimation procedure to uniquely identify the model. Since our dependent
364 variable is continuous it is justified to employ a linear equation with quadratic terms for the
365 continuous independent variables. By estimating a linear relationship between LSIE and the
366 explanatory variables we allow a simple procedure to calculate their marginal effect on LSIE. In
367 addition, because several of the dependent variables are dichotomous, we can include them in the
368 estimated relationship only as dummies.

369 The variables *Scr*, *Irr*, *Suw*, *Dev* are dichotomous variables and are introduced in the
370 estimated equation as dummies that affect the level of the intercept (constant) of the estimated
371 equation. *Reg* and *Lit* are introduced as linear ranking variables. *Pop* and *Dep* are introduced in
372 linear and quadratic forms, due to the expectation that their marginal impact on LSIE would be
373 marginally diminishing or increasing, respectively.

374 The general expression in [4] was transformed into explicit functions with linear terms for
375 the non-continuous variables (*Scr*, *Irr*, *Suw*, *Lit*, *Reg*, *Dev*), and linear and quadratic terms for the
376 continuous variables (*Pop*, *Dep_j*, $j=1, 2$) as can be seen in equation [5], and two interactive terms
377 *Irr*×*Suw* and *Dev*×*Reg*. Just to reiterate, it has to be considered that a quadratic variable with linear
378 and quadratic terms indicates that the effect of that variable (whether positive or negative) on the
379 dependent variable could be either marginally diminishing (if the coefficient of the quadratic term
380 is negative) or marginally increasing (if the coefficient of the quadratic term is positive).

381 The general empirical version of the estimated relationship is as follows:²

382

$$\begin{aligned} 383 \text{LSEI}_j^k &= \alpha_j^k + \beta_j^k \cdot \text{Scr} + \gamma_j^k \cdot \text{Pop} + \delta_j^k \cdot \text{Pop}^2 + \varepsilon_j^k \cdot \text{Irr} + \theta_j \cdot \text{Suw} + \vartheta_j^k \cdot \text{Lit} + \lambda_j^k \cdot \\ 384 \text{Dep}_j &+ \xi_j^k \cdot \text{Dep}_j^2 + \mu_j^k \cdot \text{Reg} + \phi_j^k \cdot \text{irr} \times \text{Suw} + \zeta_j^k \cdot \text{Reg} \times \text{Dev} + u^k. \end{aligned} \quad [5]$$

385 where \square_j^k is any of the estimated coefficients $\alpha, \beta, \dots, \phi, \zeta$, $j=1, 2$ stands for the two versions of
386 groundwater depletion variables that were defined earlier, and k stands for any possible version of

² The estimated coefficients of Equation [5] are used to infer our hypotheses, as they were spelled out in section 4.

387 this equation, such as a version that is solely linear (excluding the quadratic terms of Pop^2 and
388 Dep_j^2 ($j=1, 2$), or a version that does not include certain explanatory variables). u^k is the error
389 term. We employed the software Stata 13 to estimate the various model equations.

390 To keep the values of the independent variables within similar scales, we transformed Pop
391 from persons to thousands of persons $PopK=Pop/1000$ and Dep_2 from mm (as is in the original
392 dataset) to meters: $Dep_2K=Dep_2/1000$.

393 The weights of the ten attributes that we obtained from the Delphi technique are presented
394 in section 6.1.

395

396 **6. Results**

397 The analysis in this paper utilizes only 113 of the 119 observations, due to missing values of
398 depletion of groundwater in aquifers in some of the sites and due to one outlier observation (The
399 Mekong Delta). One possible explanation for being an outlier is that the observation in the Mekong
400 Delta (serving 10.7 million people) spans over a very wide region with many different geological,
401 hydrological, and social/economic conditions that could lead to unexpected behavior of LS effects.
402 Therefore, we decided to remove that observation from our dataset and continue with 113
403 observations for the statistical analysis.

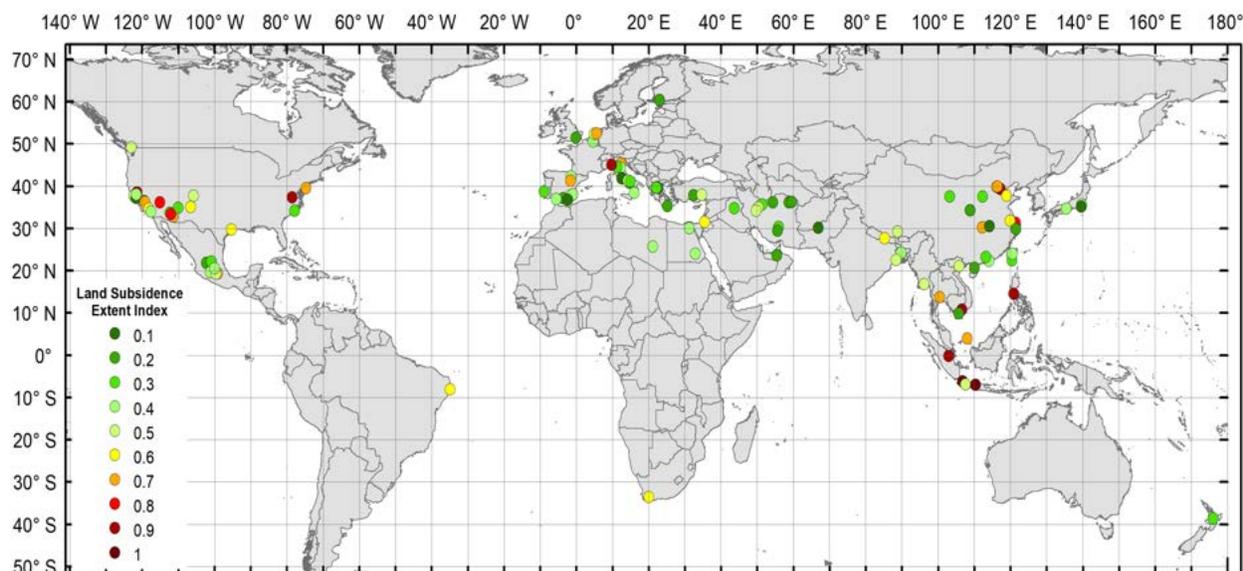
404

405 *6.1 Land Subsidence Sites and their Attributes*

406 A map with all sites that were identified in our literature review and included in the dataset with
407 LS impacts is presented in Figure 1.

408

409 <Figure 1 About Here>



410
411 Figure 1: Global impact extent of land subsidence in sites in the dataset.

412 Source: Authors' elaboration.

413 **NOTE for production (if accepted): This figure should be produced in color.**

414
415 A distribution of the 10 land subsidence attributes that comprise the LSIE, based on what
416 has been reported for the various locations in our dataset, is presented in Table 2. The values in
417 the column "Mean" should be interpreted as the frequency of each of the LSIE attributes in the
418 regions with LS impacts. Remember that attributes are non-mutually exclusive, so that some
419 locations may experience one attribute, some may experience 10 attributes, and some may
420 experience anywhere between 1 and 10 attributes. Because all locations in our dataset face LS
421 effects, there is no location reporting 0 attributes.

422
423 <Table 2 About Here>

424 Table 2: Distribution of land subsidence attributes across the sites in the dataset.

LSIE Impact Attributes	Mean	SD	CV (%)
1. Socio-economic impacts, such as structural damages	0.771	0.422	54.7
2. Environmental damages, such as malfunctioning of drainage systems	0.593	0.493	83.1
3. Geological-related damage altering subsurface lateral water flow direction	0.568	0.497	87.5

4. Environmental damages, such as reduced performance of hydrological systems	0.568	0.497	87.5
5. Environmental damages, such as wider expansion of flooded areas	0.559	0.499	89.2
6. Hydrogeological damages that result in groundwater storage loss	0.551	0.500	90.7
7. Impact on adaptation ability to climate change	0.297	0.459	154.5
8. Groundwater contamination	0.229	0.422	184.2
9. Loss of high-value transitional areas (e.g., saltmarshes)	0.127	0.335	263.8
10. Shift of land use to poorer activities	0.110	0.314	285.4

425 Note: A more detailed description of each impact attribute can be found in the introduction section.

426

427 The results in Table 2 suggest that the most common impact attribute that was identified in
428 the literature we reviewed reported in 77% of the cases as socioeconomic impacts of LS, while the
429 least common impact attribute, reported in 11% of the cases, is shift of land use to poorer activities.
430 Impact attributes 1-6 show frequency of 55-77%, while impact attributes 7-10 are relatively rare
431 (11-30%). An interesting result in Table 2 is that impact attributes with higher occurrence levels
432 are also characterized with a lower coefficient of variation (CV), indicating a lower degree of
433 variability. For example, the socioeconomic impacts of LS (mean of 0.771) are characterized with
434 a CV of 54.7, while shifts of land use to poorer activities (mean of 0.110) are characterized with a
435 much higher CV equal to 285.4. Yet, these CV values are considered relatively small and, thus,
436 the mean is representative of the sample.

437 The weights of the ten attributes resulting from the Delphi technique are presented in Table
438 3.

439

440 <Table 3 About Here>

441 Table 3: LSIE-W weights (percent) of the ten attributes as obtained from the Delphi technique
442 (sum=100)

LS Attribute									
1	2	3	4	5	6	7	8	9	10
Weights (Percent)									
18.111	10.778	2.778	6.667	22.777	12.556	9.556	7.667	5.222	3.888

443

444

445 *6.2 Descriptive Statistics*

446 Table 3 presents the descriptive statistics of the change in groundwater level change (m) over the
447 50 years from 1960 to 2010. A few aquifer systems show an increase in water table level, while
448 most show depletion. Mean depletion over the 50 years was 12.11 m. The decadal results are
449 interesting by themselves because it is very clear that the mean decline increases from 0.89 meter
450 per decade in 1960-1970, to 3.61 m per decade in 2000-2010. In addition, the standard deviation
451 of depletion increases as well over the five decades from 2.23 m to 9.21 m. Both trends suggest
452 that the long-term effects of pumping groundwater will most likely result in a higher likelihood of
453 land subsidence, as reflected in the LSIE.

454

455 <Table 3 About Here>

456 Table 3: Descriptive statistics of decadal groundwater level change (m per decade) between 1960-
457 2010 in the various aquifer systems of the dataset.

Decade	1960_2010	1960_1970	1970_1980	1980_1990	1990_2000	2000_2010
Mean	-12.11	-0.89	-1.81	-2.65	-2.91	-3.61
SD	32.14	2.23	5.86	7.65	7.96	9.21
Min	-239.38	-14.92	-51.43	-66.04	-61.18	-54.66
Max	0.59	0.33	0.48	0.51	1.46	0.75

458 Note: Negative values (Mean and Min) indicate a decline, positive values (Max) indicate an
459 increase.

460

461 The mean decline of groundwater level is more than 12 meters during 1960-2010. Decadal
462 variation of groundwater depletion level ranges between a decline of 66 meters, and a 1.5-meter
463 increase.

464

465 <Table 4 About Here>

466 Table 4: Descriptive statistics of variables considered for the regression analysis.

Variable	Description (units)	Mean	Standard Deviation	Minimum	Maximum
<i>LSIE-EW</i>	Land Subsidence	0.444	0.227	0.1	1

	Extent Index with equal weights (Real number between 0.1-1.0)				
<i>LSIE-W</i>	Land Subsidence Extent Index with weights (Real number between 0.028- 0.960)	0.508	0.247	0.028	0.960
<i>SCR</i>	Water scarcity (Dichotomous)	0.964	0.186	0	1
<i>PopK</i>	Population change (1000 people per year)	92.856	212.353	-3.529	1384.200
<i>Irr</i>	Irrigation water use (Dichotomous)	0.619	0.487	0	1
<i>Suw</i>	Available surface water (Dichotomous)	0.451	0.499	0	1
<i>Reg</i>	Effective GW regulations (Ranking)	1.761	0.735	1	3
<i>Lit</i>	Lithology (Ranking)	1.460	0.762	1	3
<i>Dep₁K</i>	GW depletion 1960-2010 (meters)	12.11	0.301	-0.041	239.38
<i>Dep₂</i>	GW periodical depletion (meters/decade)	-6.470	-17.776	-112.430	13.922
<i>Dev</i>	Developing Country (Dichotomous)	0.487	0.502	0	1

467 Note: For the continuous variables negative values indicate decrease and positive values indicate
468 increase.

469 Number of observations is 113.

470
 471 Results in Table 4 indicate that, LSIE-EW mean level in our dataset is 0.444, which
 472 suggests 4-5 attributes per location. LSIE-W mean level in the dataset is 0.508, suggesting 5
 473 attributes per location. A total of 96% of the locations in the analysis face water scarcity, which
 474 makes this variable irrelevant for the statistical analysis due to lack of variance; 62% of the regions
 475 have irrigation projects that also utilize a groundwater source; only 42% of the regions have access
 476 to surface water; the mean lithology is between Class 1 and Class 2, suggesting that aquifer systems
 477 in our dataset are prone to LS. The mean regulation ranking is 1.761, which suggests that, on
 478 average, regulation of groundwater pumping occurs but it is not effective. Finally, nearly 50% of
 479 the regions experiencing LS in our sample are in developing countries.

480
 481 *6.3 Estimation Results*

482 We estimated models of LSIE causes. We used two versions of LSIE as the dependent variable:
 483 LSIE-EW and LSIE-W. The variable *Dep₁K* was not significant in any of the estimations and is
 484 not included in the results. Models 2 and 4, include the regulatory variable *Reg*, while models 1
 485 and 3 do not include this variable. Furthermore, all models include also the interaction terms of
 486 *Irr*×*Suw* and *Dev*×*Reg*. Estimation results are presented in Table 5.

487
 488 <Table 5 About Here>

489 Table 5: Results of the LSIE equation estimates.

Model	1	2	3	4
	LSIE-EW	LSIE-EW	LSIE-W	LSIE-W
<i>Intercept</i>	0.565 (9.29)***	0.620 (7.91)***	0.651 (9.75)***	0.673 (7.77)***
<i>PopK</i>	1.057E-03 (3.49)***	1.014E-03 (3.32)***	9.869E-04 (2.96)***	9.699E-04 (2.88)***
<i>PopKsq</i>	-8.082E-07 (-3.03)***	-7.667E-07 (-2.85)***	-7.872E-07 (-2.69)***	-7.709E-07 (-2.60)***
<i>Reg</i>	-	-0.031 (-1.12)	-	-0.012 (-0.40)
<i>Suw</i>	-0.176 (-2.57)***	-0.183 (2.65)***	-0.142 (-1.88)**	-0.144 (-1.90)**
<i>Lit</i>	-0.053 (-1.79)**	-0.053 (-1.81)**	-0.0590 (-1.84)**	-0.059 (-1.85)**

<i>Dep₂</i>	6.040E-03 (2.00)**	5.962E-03 (1.98)**	7.134E-03 (2.15)**	7.10E-03 (2.14)**
<i>Dep_{2sq}</i>	5.99E-5 (1.96)**	6.043E-05 (1.98)**	7.759E-05 (2.31)**	7.777E-05 (2.30)**
<i>Irr×Suw</i>	0.106 (1.46)*	0.115 (1.57)*	0.051 (0.65)	0.055 (0.68)
<i>Dev×Reg</i>	-0.051 (-1.91)**	-0.049 (1.84)**	-0.055 (-1.90)**	-0.055 (-1.86)**
Observations	113	113	113	113
Adjusted R-Square	0.114	0.116	0.091	0.084
F-test	2.804***	2.640***	2.410***	2.143**

490 Note: in parentheses are t-statistic. *, **, and *** indicate significance at 10, 5, and 1%,
491 respectively.

492

493 In general, the results of the various estimated models (Table 5) support our different a-
494 priori hypotheses. All estimated coefficients have the expected sign, they show robustness across
495 the models, they are significant at 1 to 10%. Adjusted R-square values of the 4 estimated equations
496 range between 8 and 12%, which is reasonable for a dataset that includes variables that were
497 collected from various sources. The F-tests are significant at the 1% level for models 1 to 3 and at
498 the 5% level for Equation 4. The fact the models with the two dependent variables—LSEI-W and
499 LSEI-EW—resulted in very, statistically, similar sets of coefficients indicates a high level of
500 robustness of our analytical framework.

501 For all models the population variable indicates a quadratic effect with *PopK* being positive
502 and *PopKsq* being negative, which indicates a quadratic effect on LS. Because *PopKsq* is very
503 small, the quadratic effects on LSIE are monotonic. But, in general for all models, the larger the
504 annual population growth trend the greater is the extent of LS, and this effect is incrementally
505 declining with the increase in population growth.

506 The variable *Reg*, measuring effectiveness of regulatory policies, has a negative coefficient
507 suggesting that as regulations become more effective, LSIE is reduced. However, the estimated
508 coefficients of this variable are not significant. Suspecting that level of effectiveness of
509 groundwater regulatory policies is also affected by the overall level of water governance in the
510 country, we introduced the interaction variable *Dev×Reg*, which measures the effect of overall
511 governance and the specific effect of groundwater management regulatory policies. The

512 coefficient of the interaction term is negative and significant in all models, suggesting that in
513 developing countries and in regions with effective policies, the level of LSIE is lower.

514 The variable Suw , which indicates whether or not there is a source of surface water to
515 satisfy the needs of the region, in addition to groundwater, has a negative and significant
516 coefficient. This means that having an additional surface water source releases the pressure on
517 aquifers, which translates into a lower LSIE. However, an interaction term $Irr \times Suw$ was also
518 introduced to capture the possible effect of utilization of the surface water source for irrigation and
519 creating pressure on the region. Estimated coefficients in Table 5 suggest that this interaction term
520 has a positive sign, suggesting that both irrigation site and a source for surface water used for
521 irrigation will increase the level of LSIE, suggesting that having the additional source of surface
522 water used for irrigation introduces additional pressure on the water resources in the site. This
523 interaction term is significant at 10% level in models 1 and 2 (LSIE-EW).

524 The Lit variable, characterizing the lithology type of aquifer systems suggests that higher
525 levels of the lithology ranking (Table 1), which means a stiffer aquifer system, is associated with
526 lower LSIE. The estimated coefficients of the Lit variable are significant at 5% in all models).

527 Finally, the decline of groundwater level is modeled as a quadratic relationship. We use
528 the variable Dep_2 . In all models both the linear component (Dep_2) and the quadratic component
529 (Dep_2sq) are positive and significant, which means that the effect of groundwater level depletion
530 on land subsidence extent increases in an increased rate.

531

532 **7. Policy Simulations**

533 Several of the variables in the investigated models provided in Table 5 could be considered for
534 policy intervention options using the sign and value of the regressors to quantify their incremental
535 effects. To keep the paper length, we will demonstrate the effects of policy impacts using model 1
536 only. The analysis includes the effects of population change (Pop), access to surface water (Suw),
537 reduction in GW level (Dep), and indirectly the interactions between governance level and
538 regulation effectiveness ($Dev \times Reg$) and between access to surface water and irrigation ($Sue \times Irr$).

539 We conduct two simulations: First we analyze marginal effects, using mean values of the
540 relevant variables, and then we conduct a ‘with and without’ analysis of those variables.

541

542 *7.1 Marginal effect of policy interventions*

543 Each of the marginal effects below is analyzed, assuming all other remain unchanged. The
 544 marginal effect of population change, which represents pressure on the aquifer system, is
 545 determined by $\frac{\partial LSEI}{\partial Pop} = 0.001057 - 2 \cdot 8.082 \cdot 10^{-7} \cdot \overline{PopK}$, where \overline{PopK} is the sample mean
 546 (=92.856). The calculation of the incremental effect of population change at the sample mean
 547 yields $\frac{\partial LSEI}{\partial Pop} = 0.0009085$. This means that the incremental effect of population growth, will result
 548 in an increase of nearly 0.0009 units of the land subsidence extent or less than 0.1%.

549 The marginal effect of access to surface water source is measured as $0.1058 \cdot \overline{Irr}$, where
 550 \overline{Irr} is the sample mean (=0.619) of having the irrigation sector use of such water. The calculation
 551 yields a marginal effect that equals 0.065. This means that having access to a surface water source
 552 used for irrigation, in addition to the aquifer water will result in an increase in the land subsidence
 553 impact extent of nearly 0.065 units, or 6.5%.

554 The marginal effect of groundwater level depletion is measured by $\frac{\partial LSEI}{\partial Dep_2} = 0.00604 + 2 \cdot$
 555 $5.997 \cdot 10^{-5} \cdot \overline{Dep_2}$, where $\overline{Dep_2}$ is the sample mean (= -6.470). The calculation of the
 556 incremental effect of groundwater level depletion at the sample mean yields $\frac{\partial LSEI}{\partial Dep_2} = 0.00526$. This
 557 means that the incremental effect of the groundwater level depletion will result in an increase of
 558 nearly 0.0053 units of the land subsidence extent, or nearly 0.5%.

559 The marginal effect of the variable that measures interaction between regulation
 560 effectiveness and level of governance is $-0.051 \cdot \overline{Dev}$, where \overline{Dev} is the sample mean (=0.487).
 561 This means that the increase in groundwater regulations and governance, in general, will result in
 562 a reduction of the land subsidence extent of nearly 0.025 LSIE units. Due to the measurement of
 563 LSIE, this means a reduction of nearly 2.5%.

564 To sum up, the marginal effects of regulation (*Reg*), population (*PopK*), groundwater level
 565 depletion (*Dep₂*), and of access to surface water source (*Suw*) on the LSIE-W are -0.025,
 566 +0.0009085, +0.0053, and +0.065, respectively, with a total sum of the marginal effects of -0.013,
 567 or nearly 1.5%. This also means that the variables included in our estimation have opposite effects
 568 on land subsidence and, thus, policy interventions with opposed effects should be carefully
 569 considered. In addition, the variable with the most measurable effect (of nearly 10%) is the
 570 existence of a source of surface water supply, which for our purposes could also be any other

571 source of manufactured water. This result provides a direction for prioritizing policies for
 572 addressing land subsidence. This set of considerations will be discussed in the next section.

573
 574 *7.2 With and without effects*

575 Under the with and without analysis we use the mean value for the continues variables (*Pop*, and
 576 *Dep*) and for the ranking variables (*Lit*, and *Reg*) while we switch between 1 and 0 to account for
 577 ‘with’ and ‘without’, respectively for *Dev*, *Irr* and *Suw*. Results are presented in Table 6.

578
 579 Table 6: Impact of dichotomous variables on level of LSIE-EW using ‘with and without’ effects.

Senario	1	2	3	4	5	6	7	8
	SUW=1	SUW=0	SUW=1	SUW=1	SUW=0	SUW=0	SUW=0	SUW=1
	IRR=1	IRR=0	IRR=0	IRR=1	IRR=1	IRR=1	IRR=0	IRR=0
	DEV=1	DEV=0	DEV=1	DEV=0	DEV=1	DEV=0	DEV=1	DEV=0
LSIE-EW	0.3829	0.3667	0.2769	0.4727	0.4529	0.5427	0.4529	0.4708

580
 581 Notes:

582 (1) Equation used: $LSIE-EW=0.565+0.001057*POP-0.000000808*POP*POP-0.176*SUW-$
 583 $0.053*LIT+0.00596*DEP+0.0000604*DEP*DEP+0.106*IRR*SUW-0.051*DEV*REG$

584 (2) Mean values used for continuous variables: POP=92.856; LIT=1.46; DEP=-6.47; REG=1.761.

585
 586 Results in Table 6 shows that the level of LSIE-EW is sensitive to the combination of the
 587 dichotomous variable that indicated access to surface water sources, competition between the
 588 urban and the irrigated sector, and whether or not the country under which land subsidence occurs
 589 is a developed or developing one.

590 Indeed, it appears that for all combinations of the 3 control variables, the impact of having
 591 an irrigation project resulted in a higher level of LSEI-EW, suggesting higher stress on the
 592 groundwater resources when irrigation is present. In the same way it is evident that the level of
 593 land subsidence impact is higher when access to surface water resources are not available and the
 594 locality relies only on the aquifer water.

595
 596 **8. Discussion, Policy Implications, and Limitations**

597 In spite of its major social cost in hundreds of locations around the world, the majority of which
598 have irreversible negative physical and economic impacts, land subsidence has not been given
599 proper preventive attention by regulatory agencies and local water management organizations in
600 many countries. We were able to identify and analyze land subsidence effects in 113 locations
601 where mainly physical consequences of land subsidence have been assessed but economic
602 damages, likely in the range of billions of dollars, have not been quantified. In the absence of a
603 method for estimating economic value for the LS-induced damage, we developed a land
604 subsidence extent index (LSIE) that relies on the occurrence of up to 10 land subsidence effects
605 that were observed in these sites. This assessment allows the identification of different types of
606 impacts in different locations and is used to explain the effects of physical conditions, such as
607 aquifer lithology, managing institutions, social systems, existing policies, population pressure,
608 water-level depletion from over pumping, and several other variables on LSIE. While this
609 approach may lead to a comparative assessment of the impact of land subsidence across sites, we
610 are aware of its limitations as a measure for land subsidence for comparing damages and impacts
611 across sites.

612 The results of our analysis indicate the importance of effective policy regulations on
613 reducing impact of land subsidence, captured in lower values of LSIE. Our results suggest also
614 that developing countries are more prone to higher levels of LSIE, mainly because of mal-
615 performing institutions and lesser success of the governance system. This suggests that improving
616 groundwater management in developing countries may be more beneficial once the negative
617 impacts of land subsidence are considered. In addition, a general conclusion from this analysis is
618 that more resources and efforts should be allocated by international agencies to the systematic and
619 comparative analysis of drivers of land subsidence and measurements of land subsidence economic
620 impacts.

621 The results obtained in this study may provide useful insights for policy implications such
622 as that policies for groundwater regulation could be less effective for land subsidence in
623 developing countries than in developed countries. This suggests that a more rigorous regulatory
624 intervention approach should be considered for countries with malfunctioning institutions and
625 lower levels of governance. We also can derive several lessons regarding the need to establish
626 policies that consider development of various water resources and their conjunctive use in order
627 to ease pressure on the aquifer systems in regions under risk of land subsidence. This includes

628 importing surface water, developing or investing in technologies (desalination of brackish or
629 seawater, treating wastewater) to amend water supply to the regions, policies for curbing
630 groundwater extractions, developing programs to introduce incentives for recharge of various
631 types of water into the aquifer in years of supply abundance, and instituting the framework to allow
632 water trade within and between regions that face risk of land subsidence.

633 Several limitations of our study should be mentioned. First, in an absence of exact number
634 of the population relying on the aquifer system and the size of the aquifer system in question, we
635 can introduce a bias to the LSIE calculation. Second, we have used for the calculation of population
636 growth rate an acceptable range of years (1995-2015) within which the land subsidence reported
637 in the regions in our sample have taken place. However, it could well be that significant increase
638 in the population in these regions started much earlier and triggered the impacts on the aquifer
639 systems. Therefore, results regarding population growth have to be cautiously viewed.

640 One important aspect that we were not able to accomplish in our work is to compare our
641 results with those obtained in previous similar studies. This is unfortunately impossible to obtain
642 mainly due to the innovative nature of our approach in developing a global index for land
643 subsidence extent. All known studies that estimate physical impact or even economic impact of
644 land subsidence are limited to one region, or several regions within one country, and thus cannot
645 be compared with global findings. One study that could be considered the closest to our work in
646 terms of global assessment of land subsidence impacts, the Herrera-Garcia et al. (2021), evaluates
647 the impacts in terms of general, state-level, welfare losses, while we look at LS site-specific effects.

648 Our plan of research for the coming years is to develop a framework to estimate the total
649 effects of land subsidence and to apply it to a series of studies in different parts of the world. This
650 will allow building a set of comparable case studies that will facilitate the aggregation of economic
651 effects of land subsidence in various parts of the world.

652
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666

667 **9. References**

- 668 Borchers H.L., and M. Carpenter, 2014. Land Subsidence from Groundwater Use in California.
669 California Water Foundation, Summary Report, April.
- 670 Béjar-Pizarro, M., M. Ezquerro, G. Herrera, R. Tomás, C. Guardiola-Albert, J.M., Ruiz Hernández,
671 J.A., Fernández Merodo, M. Marchamalo & R. Martínez, 2017. Mapping groundwater level
672 and aquifer storage variations from InSAR measurements in the Madrid aquifer, Central
673 Spain. *Journal of Hydrology*, 547:678-689, doi:
674 <http://doi.org/10.1016/j.jhydrol.2017.02.011>.
- 675 Bonì, R., G. Herrera, C. Meisina, D. Notti, M. Béjar-Pizarro, F. Zucca, P. J., González, M. Palano,
676 R. Tomás, J. Fernández, J. A. Fernández-Merodo, J. Mulas, R. Aragón, C. Guardiola-Albert,
677 and O. Mora, 2015. Twenty-year advanced DInSAR analysis of severe land subsidence:
678 The Alto Guadalentín Basin (Spain) case study. *Engineering Geology*, 198, 40-52, doi:
679 <http://dx.doi.org/10.1016/j.enggeo.2015.08.014>.
- 680 Bru, G., G. Herrera, R. Tomás, J. Duro, J., R. De la Vega, and J. Mulas, 2013. Control of
681 deformation of buildings affected by subsidence using persistent scatterer interferometry.
682 *Structure and Infrastructure Engineering* 9: 188-200. doi: 10.1080/15732479.2010.519710
- 683 Díaz, E., P. Robles, and R. Tomás, 2018. Multitechnical approach for damage assessment and
684 reinforcement of buildings located on subsiding areas: Study case of a 7-story RC building
685 in Murcia (SE Spain). *Engineering Structures*, 173:744-757.
- 686 Dinar, A., E. Esteban, E. Calvo, G. Herrera, P. Teatini, R. Tomás, Y. Li, and J. Albiac, 2020. Land
687 subsidence: The forgotten enigma of groundwater (over-) extraction. Paper presented at
688 the AERE/ASSA 2020 Allied Social Sciences Associations Annual Meeting, San Diego,
689 CA, January 3-5, 2020. Retrieved from
690 https://www.aeaweb.org/conference/2020/preliminary/2093?q=eNqrVipOLS7OzM8LqSxIVbKqhnGVrJQMIWp1lBKLi_OTgRwlHaWS1KJcXAgrJbESKpSZmwphlWWmloOOFxUUXDAFTA1AegsS00Gylkq1XDButx4c on 22 September 2020.
- 693 Döll, P., H. Müller Schmied, C. Schuh, F.T. Portmann, and A. Eicker, 2014. Global-scale
694 assessment of groundwater depletion and related groundwater abstractions: Combining
695 hydrological modeling with information from well observations and GRACE satellites,
696 *Water Resources Research*, 50, doi:10.1002/2014WR015595.

697 Erkens, G., T. Bucx, R. Dam, G. de Lange, and J. Lambert, 2015. Sinking coastal cities,
698 *Proceedings of the International Association of Hydrological Sciences*, 372:189–198,
699 <https://doi.org/10.5194/piahs-372-189-2015>.

700 Erkens, G., M.J. van der Meulen, and H. Middelkoop, 2016. Double trouble: subsidence and CO2
701 respiration due to 1,000 years of Dutch coastal peatlands cultivation. *Hydrogeology*
702 *Journal*, 24, 551-568, doi: 10.1007/s10040-016-1380-4.

703 Fiksel, J., T. Eason and H. Frederickson, 2012. Framework for Sustainability Indicators at EPA.
704 Office of Research and Development, National Risk Management Research Laboratory,
705 U.S. Environmental Protection Agency. Washington DC: EPA.

706 Freeze, R. A., 2000. Social decision-making and land subsidence. In: SISOLS 2000, *Proceedings*
707 *of the Sixth International Symposium on Land Subsidence*, Vol. I, L. Carbognin et al. eds.,
708 La Garangola, Padova, Italy, 353-384.

709 Gabrielsen, P. and P. Bosch, 2003. Environmental Indicators: Typology and Use in Reporting.
710 European Environment Agency Internal Working Paper. Copenhagen: European
711 Environment Agency.

712 Galassi, G., F. Levarlet, 2017. Improving sustainability of programmes in strategic environmental
713 assessment procedures: The QUALitative Structural Approach for Ranking (QUASAR) the
714 environmental effects. *European Journal of Sustainable Development*, 6(1):233-246–246.

715 Galloway, D.L., G. Erkens, E.L. Kuniatsky, et al., 2016. Preface: Land subsidence processes.
716 *Hydrogeology Journal* 24:547–550. <https://doi.org/10.1007/s10040-016-1386-y>.

717 Gambolati, G., and P. Teatini, 2015. Geomechanics of subsurface water withdrawal and injection.
718 *Water Resources Research*, 51(6):3922-3955.

719 Gambolati, G., P. Teatini, and M. Ferronato, 2005. Anthropogenic land subsidence. In:
720 *Encyclopedia of Hydrological Sciences*, M. G. Anderson ed., John Wiley & Sons,
721 Chichester (UK), Vol. 4, Chapter 158, 2443-2459.

722 Hartmann, J., and N. Moosdorf, 2012. The new global lithological map database GLiM: A
723 representation of rock properties at the Earth surface. *Geochemistry Geophysics*
724 *Geosystems*. 13(12), <https://doi.org/10.1029/2012GC004370>.

725 Heri, A., H. Z. Abidin, D. A. Sarsito, and D. Pradipta. 2018. Adaptation of ‘early climate change
726 disaster’ to the northern coast of Java Island Indonesia. *Engineering Journal*, 22(3):207-
727 219.

728 Herrera-Garcia, G. et al. (18 additional co-authors), 2021. Mapping the global threat of land
729 subsidence. *Science*, 371(6524):34-36.

730 Holzer, T.L., and D.L. Galloway, 2005. Impacts of land subsidence caused by withdrawal of
731 underground fluids in the United States. *Reviews in Engineering Geology*, XVI:87-99.

732 Jones, L.L., and J. Larson, 1975. Economic Effects of Land Subsidence Due to Excessive
733 Groundwater Withdrawal in the Texas Gulf Coast Area. Texas Water Resources Institute
734 TR-67 1975.

735 Kok, S., and A.L. Costa, 2021. Framework for economic cost assessment of land subsidence.
736 *Natural Hazards*. <https://doi.org/10.1007/s11069-021-04520-3>

737 Lixin, Y., W. Jie, S. Chuanqing, J. Guo, J. Yanxiang, and B. Liu, 2010. Land subsidence disaster
738 survey and its economic loss assessment in Tianjin, China. *Natural Hazards Review*, 11,
739 35-41, doi: doi:10.1061/(ASCE)1527-6988(2010)11:1(35).

740 Notti, D., R.M. Mateos, O. Monserrat, N. Devanthery, T. Peinado, F.J. Roldán, F. Fernandez -
741 Chacón, J. Pedro Galve, F. Lamas, and J. Miguel Azañón, 2016. Lithological control of
742 land subsidence induced by groundwater withdrawal in new urban areas (Granada Basin,
743 SE Spain). *Hydrological Monitoring*, 34(13): 2317-2331.
744 <https://doi.org/10.1002/hyp.10793>.

745 OECD (Organisation for Economic Co-operation and Development), 2003. OECD Environmental
746 Indicators: Development Measurement and Use. Paris: OECD.

747 Poland, J.F., 1984. Guidebook to studies of land subsidence due to groundwater withdrawal.
748 United Nations Educational, Scientific and Cultural Organization, MI: Chelsea.

749 Purvis, L., and A. Dinar, 2020. Are intra- and inter-basin water transfers a sustainable policy
750 intervention for addressing water scarcity? *Water Security*, 9:100058.

751 Saleth, M.R., and A. Dinar, 2004. *The Institutional Economics of Water: A Cross-Country Analysis
752 of Institutions and Performance*. Cheltenham: Edward Elgar.

753 Sanabria, M.P., C. Guardiola-Albert, T. Tomás, G. Herrera, A. Prieto, H. Sánchez, and S. Tessitore,
754 2014. Subsidence activity maps derived from DInSAR data: Orihuela case study. *Natural
755 Hazards and Earth System Sciences*, 14, 1341-1360, doi: 10.5194/nhess-14-1341-2014.

756 Singh, C., H. Osbahr, and P. Dorward, 2018. The implications of rural perceptions of water scarcity
757 on differential adaptation behaviour in Rajasthan, India. *Regional Environmental Change*,
758 18:2417–2432.

759 Teatini, P., D. Carreón-Freyre, G. Ochoa-González, S. Ye, D. Galloway, and M. Hernández-Marin,
760 2018. Ground ruptures attributed to groundwater overexploitation damaging Jocotepec city
761 in Jalisco, Mexico: 2016 field excursion of IGCP-641, *Episodes*, 41(1):69-73.

762 Tomás, R., G. Herrera, G. Cooksley, and Mulas, J. 2011. Persistent scatterer interferometry
763 subsidence data exploitation using spatial tools: The Vega Media of the Segura River Basin
764 case study. *Journal of Hydrology*, 400, 411-428.

765 Tomás, R., J. García-Barba, M. Cano, M.P. Sanabria, S. Ivorra, J. Duro, and G. Herrera, 2012.
766 Subsidence damage assessment of a gothic church using Differential Interferometry and
767 field data. *Structural Health Monitoring*, 11, 751-762.

768 Tomás, R., Y. Márquez, J.M. Lopez-Sanchez, J. Delgado, P. Blanco, J.J. Mallorquí, M. Martínez,
769 G. Herrera, and J. Mulas, 2005. Mapping ground subsidence induced by aquifer
770 overexploitation using advanced differential SAR interferometry: Vega Media of the
771 Segura River (SE Spain) case study. *Remote Sensing of Environment*, 98:269-283.

772 Viets, V.F., C.K. Vaughan, and R.C. Harding, 1979. Environmental and economic effects of
773 subsidence. Earth Sciences Division, Lawrence Berkeley Laboratory, University of
774 California, Publication LBL-8615 GSRMP-I UC-66e. Accessed at
775 <https://escholarship.org/uc/item/1sb4c8vh> on February 16, 2021.

776 Wade, C.M., K.M. Coborun, G.S. Amacher, and E.T. Hester, 2018. Policy targeting to reduce
777 economic damages from land subsidence. *Water Resource Research*, 54:4401-4416.

778 Warren, J.P., L.L. Jones, R.D. Lacewell, and W.L. Griffin, 1975. External costs of land subsidence
779 in the Huston-Baytown area. *American Journal of Agricultural Economics*, 57(3):450-455.

780 Yoo, J., and C. Perrings, 2017. An externality of groundwater depletion: Land subsidence and
781 residential property prices in Phoenix, Arizona, *Journal of Environmental Economics and*
782 *Policy*, 6(2):121-133, doi:10.1080/21606544.2016.1226198.

783 Zhou, C., H. Gong, B. Chen, X. Li, J. Li, X. Wang, M. Gao, Y. Si, L. Guo, M. Shib, and G. Duan,
784 2019. Quantifying the contribution of multiple factors to land subsidence in the Beijing
785 Plain, China with machine learning technology. *Geomorphology*, 335:48-61.

786 Zoccarato, C., P.S.J. Minderhoud, and P. Teatini, 2018. The role of sedimentation and natural
787 compaction in a prograding delta: Insights from the mega Mekong delta, Vietnam,
788 *Scientific Reports*. 8, 11437, doi:10.1038/s41598-018-29734-7.

789

790 **Appendix A: Table A1.** Summary of the survey and analysis of literature LS impacts,
 791 definitions, impact evaluation, proxy variables, and results.
 792

LS attributes	References	Impact evaluation	Proxi variables in LSIE [0.1,1.0]	Results	
3. Geological-related damages: Effects on underground lateral water flows	[3]	Aquifer lithology and hydrogeology			
6. Hydrogeological damages resulting in groundwater storage loss	[4]	Physical factors	Lit [1/2/3]	\nearrow Lit \nearrow LSIE	
5. Environmental damages: Such as wider expansion of flooded areas	[3]	Water level Depletion Physical factors	Scr [0/1]	Not included due to non-variability	
4. Environmental damages: Such as reduced performance of hydrological systems	[3]		Pop (numerical)	\nearrow Pop \nearrow LSIE Pop \cap	
8. Groundwater contamination such as seawater intrusion resulting in decrease of farmland productivity	[3], [4]		Irr [0/1]	Non-significant \nearrow Irr \searrow LSIE	
2. Environmental damages: malfunctioning of drainage systems	[2]		Suw [0/1]	\nearrow Suw \searrow LSIE \nearrow Irr x Suw \nearrow LSIE	
7. Impact on adaptation ability to climate change	[5]		Dep (numerical)	\nearrow Dep \nearrow LSIE Dep \cup	
9. Loss of high-value areas	[2]		Managing institutions and existing policies Social and policy factors	Reg [1/2/3] Reg x Dev	Non-significant \nearrow Reg x Dev \searrow LSIE
10. Shift of land	[6]			Dev [0/1]	\nearrow Reg \searrow LSIE
1. Socio-economic	[1]				

793
 794 Notes: Attributes in Table A1 are not in order due to need to fit the impact evaluation criteria.

795 References: [1] = Bru et al. (2013); [2] = Viets et al. (1979); [3] = Poland (1984); [4] = Holzer
 796 and Galloway (2005); [5] = Erkens et al. (2016); [6]= Heri et al. (2018).

Appendix B: Assigning weights to the LSIE attributes using the Delphi technique

Deciding on parameters to be used in analyses is always a challenge, especially when the knowledge base is narrow, or without measurable information. Regulators, politicians, managers, and public officials have been benefiting from the application of the Delphi technique – a widely used instrument to aggregate individual expert judgments into refined opinion, either to forecast future events, or to estimate current status, intentions, or parameter values. A detailed description of and discussion about the Delphi Technique can be found in various publications such as, Linstone and Turoff, (1975a, b) and Webler et al., (1991)).

The Delphi technique relies on a structured, yet indirect, approach to quickly and efficiently elicit responses relating to group learning and forecasting from experts who bring knowledge, authority, and insight to the problem, while, at the same time, promoting learning among panel members. It records facts and opinions of the panelists, while avoiding the pitfalls of face-to-face interaction, such as group conflict and individual dominance.

Several limitations have also been recognized in the application of the Delphi technique. Besides possible poor design, and execution of the process, which might affect the application of any other technique, the Delphi technique is sensitive to selection of panelists that can deliberately promote desired outcomes or influence future decisions – making the selection of panelists very important. Another disadvantage of the Delphi technique is that there is no way to assign higher or lower reliability scores to technical panelists compared with lay panelists.

The Delphi process exists on ‘iterative’ and ‘almost simultaneous’ forms. While the first form consists of a monitoring team that regulates and coordinates the process, the latter one is mechanized (computer, web), and allows real-time responses and updates. However, the Delphi process, in either form, consists of four basic phases: (a) exploration of the subject under consideration, (b) understanding how each panelist views the issue, (c) in case of disagreement, understanding the reasons for such differences, and (d) feedback, final evaluation and consensus.

We applied the Delphi process to estimating weights of the 10 land subsidence attributes that comprise the LSIE. We selected a team of 9 experts on land subsidence [from the Netherlands, China, Pakistan, Spain, Italy, California (USA), Louisiana (USA), and Virginia (USA)].

The experts were provided with a table that describes the components of the LSIE and were asked to assign weights (in %) to each (summing to 100). We used the same definitions as in the manuscript:

1. Socio-economic impacts: Damage to infrastructure
2. Environmental damages: malfunctioning of drainage systems
3. Geological-related damages: Effects on underground lateral water flows
4. Environmental damages: Such as reduced performance of hydrological systems
5. Environmental damages: Such as wider expansion of flooded areas
6. Hydrogeological damages: Resulting in groundwater storage loss
7. Impact on adaptation ability to climate change: Such as the loss of the buffer value of groundwater in years of scarcity
8. Groundwater contamination: Such as seawater intrusion resulting in decrease of farmland productivity in coastal aquifer systems and decrease of fresh-water availability
9. Loss of high-value transitional areas: Such as saltmarshes
10. Shift of land use to poorer activities: Such as from urbanized zones to rice fields, from rice fields to fish and shellfish farms, from fish farms to wastewater ponds

At the onset of the Delphi process, the 9 experts were given the basic information on the 10 attributes and their definitions. The experts were asked to assign weights to each attribute. Two co-authors of the paper administered the process and collected and analyzed the feedback from the panel experts. The process would be terminated when there is no attribute with a coefficient of variation across the experts or the mean across the 10 attributes which exceeds 50-60% (Woudenberg, 1991). The process terminated after two rounds. The data and analysis of the feedback from the experts per round are presented below.

Table B1: Data from round 1 of the Delphi technique

Expert	LSIE Attribute									
	1	2	3	4	5	6	7	8	9	10
	Percent									
1	25	25	2	2	30	4	2	4	5	1
2	15	8	1	5	25	30	5	5	5	1
3	20	15	5	5	25	5	5	5	10	5
4	20	15	2	5	25	5	10	10	5	3
5	30	8	5	5	30	7	6	5	2	2

6	10	3	1	10	20	5	30	10	6	5
7	15	10	5	10	5	15	15	15	5	5
8	15	5	10	10	15	20	0	10	5	10
9	20	10	5	5	25	15	5	5	5	5

Table B2: Descriptive statistics of the results for the LSIE attributes in Round 1 (9 experts)

	LSIE Attribute									
	1	2	3	4	5	6	7	8	9	10
CV	31.814	59.959	71.807	46.034	35.773	76.034	105.120	48.804	38.654	68.200
Mean	18.889	11.000	4.000	6.333	22.222	11.778	8.667	7.667	5.333	4.111
Standard Deviation	6.009	6.595	2.872	2.915	7.949	8.955	9.110	3.742	2.062	2.804
Standard Error	2.003	2.198	0.957	0.972	2.650	2.985	3.037	1.247	0.687	0.935
Minimum	10	3	1	2	5	4	0	4	2	1
Maximum	30	25	10	10	30	30	30	15	10	10

As can be seen from Table B2 the first round of elicitation of land subsidence attribute weights yielded coefficients of variations values in excess of 50% for 5 of the 10 attributes. In addition, the overall variation across all 10 attributes, measured via the coefficient of variation of all attributes and panel experts was 59.25%

As a result, we shared the mean weight values for the 10 attributes with the group of experts and requested that they consider modifying their weight assessment of all 10 attributes. The results of the second round of assessment is presented in Table B3.

Table B3: Data from round 1 of the Delphi technique

Expert	LSIE Attribute									
	1	2	3	4	5	6	7	8	9	10
	Percent									
1	23	20	2	5	25	8	5	5	5	2
2	15	8	1	5	25	30	5	5	5	1
3	20	14	4	5	25	7	6	6	8	5
4	20	12	2	5	25	8	10	10	5	3

5	20	10	5	5	25	10	10	8	3	4
6	10	3	1	10	20	5	30	10	6	5
7	20	10	5	10	15	10	10	10	5	5
8	15	10	0	10	20	20	5	10	5	5
9	20	10	5	5	25	15	5	5	5	5

We repeated our calculation of the coefficient of variation for all 10 LSIE attributes in Round 2. The descriptive statistics of the 10 attributes is presented in Table B4.

Table B4: Descriptive statistics of the results for the LSIE attributes in Round 2 (9 experts)

	LSIE Attribute									
	1	2	3	4	5	6	7	8	9	10
CV	21.990	42.462	71.498	37.500	15.947	63.481	83.902	31.277	24.926	39.512
Mean	18.111	10.778	2.778	6.667	22.778	12.556	9.556	7.667	5.222	3.889
Standard Deviation	3.983	4.577	1.986	2.500	3.632	7.970	8.017	2.398	1.302	1.537
Standard Error	1.328	1.526	0.662	0.833	1.211	2.657	2.672	0.799	0.434	0.512
Minimum	10	3	0	5	15	5	5	5	3	1
Maximum	23	20	5	10	25	30	30	10	8	5

As can be seen from Table B4, the values of the coefficients of variation have declined for all attributes in Round 2 compared to Round 1. The mean CV across all 10 attributes declined from 59.25% in round 1 to 43.24% in round 2. These two results led us to truncate the process of getting feedback from the 9 LS experts. The mean weights for each attribute in Table B4 were used for the calculation of the weighted LSIE in our regression analysis (rounding values beyond the decimal point to obtain a total value of 100 for the LSIE).

References

Linstone, H.A. and M. Turoff (eds) (1975a), *The Delphi Method Techniques and Applications*, Reading, MA: Addison-Wesley Publishing Company.

Linstone, H.A. and M. Turoff (1975b), 'Introduction', in H.A. Linstone and M. Turoff (eds), *The Delphi Method Techniques and Applications*, Reading, MA: Addison-Wesley Publishing Company.

Webler, T., D. Levine, H. Rakel, and O. Renn (1991), 'A novel approach to reducing uncertainty: the group Delphi', *Technological Forecasting and Social Change* 39: 253–263.

Woudenberg, F. (1991), 'An evaluation of Delphi', *Technological Forecasting and Social Change* 40: 131–150.