An analytical methodology to estimate the changes in fresh groundwater resources with sea-level rise and coastal erosion in strip-island unconfined aquifers: illustration with Savary Island, Canada

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1   **An analytical methodology to estimate the changes in fresh groundwater**

2   **resources with sea-level rise and coastal erosion in strip-island**

3   **unconfined aquifers: illustration with Savary Island, Canada**

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Abstract

Closed-form analytical solutions for assessing the consequences of climate change on fresh groundwater oceanic island lenses have been developed by hydrogeologists during the last decade. Based on existing equations, this study focuses on the case of strip oceanic islands when three combined effects of climate change are observed to affect the freshwater lens volume and its groundwater resource renewal: sea-level rise, erosion, and change in groundwater recharge rates. New equations, integrating these combined effects of climate change on fresh groundwater resources are provided. These equations are solved by a novel methodology based on a Dupuit-Forchheimer groundwater flow model that allows for determination of the hydrogeological parameters included in the equations. The approach is illustrated with the strip island of Savary, which is located along the Pacific coast of Canada in the province of British Columbia. This example illustrates, on the one hand, the volume depletion of the island freshwater lens and, on the other hand, the decrease of the renewal rate of groundwater. The proposed approach can be applied to any strip islands worldwide to assess the cumulative effects of sea-level rise and shore erosion on groundwater resources, depending on the predicted climate change scenarios. The results can then help decision-makers to anticipate the effects of climate change on the groundwater availability in strip oceanic islands and plan future groundwater use accordingly.

Keywords: Climate change, Island hydrology, Groundwater resources, Analytical solutions, Sea-level rise

1. Introduction

Small oceanic islands rely usually more on groundwater resources than surface water resources for the water supply. Ensuring water supply for oceanic island communities is a constant challenge worldwide because oceanic islands are surrounded by seawater that intrudes into the island aquifer. Freshwater contained in island aquifers is represented by a lighter freshwater lens floating above the denser saltwater. This freshwater lens is replenished by precipitation that infiltrates into the subsurface and discharges to the ocean along the island coasts. Oceanic islands can be densely populated considering their attractive environment and the pressure on fresh groundwater resources can be high, making water supply a real challenge, increased by the fact that freshwater is threaten by the surrounding seawater intrusion (Oude Essink, 2001; White and Falkland, 2010;).

Climate change makes freshwater resources in coastal environments more vulnerable (Melloul and Collin, 2006). One of the consequences of climate change is changes to the pattern and intensity of precipitation, which consequently has an impact on groundwater recharge in aquifers. In addition to the changes in precipitation, two other consequences of climate change that particularly affect coastal environments are sea-level rise and shore erosion (Terry and Falkland, 2010). Both effects amplify 'seawater intrusion' because they result in an inland progression of seawater, often called 'land-surface seawater inundation'. Depending on the climate change scenario, the cumulative effects of freshwater replenishment changes and increased seawater intrusion may have dramatic effects on water supply in oceanic island environments. For this reason, the impacts of climate change on groundwater resources in oceanic island aquifers must be anticipated depending on climate

change scenarios, in order to help decision makers plan for future possible groundwater use and to make development plans accordingly.

During the last decade, the issue of the impacts of climate change and more specifically of sea-level rise on seawater intrusion in oceanic islands has gained interest worldwide. These impacts have been investigated either with numerical modeling (Sulzbacher et al., 2012; Lemieux et al., 2015; Gulley et al., 2016) or analytical modeling (Ketabchi et al., 2014; Morgan and Werner, 2014; Chesnaux, 2016). However, most of the studies were principally numerical investigations that were conducted for cases of specific islands and their results could not be extended for general cases. Also, except for the study by Lemieux et al. (2015), the combined effects of sea shore erosion and sea-level rise on the characterization of land-surface inundation were not considered, ie only the effects of sea-level rise were investigated.

This study proposes an analytical methodology based on the previous analytical developments of Chesnaux (2016) to investigate the cumulative effects of climate change, i.e. changes in groundwater recharge rate, sea-level rise and sea shore erosion, on freshwater resources in the case of strip oceanic island unconfined aquifers. From this methodology, the effects on both the freshwater lens volume and the annual recharge (freshwater renewal capabilities) can be quantified with different scenarios of climate change. This simple methodology is first presented with the analytical equations to be used and the island hydrogeological information that is required to solve the equations. The methodology is then illustrated with the specific case of a Pacific island located on the West Coast of Canada: Savary Island, British Columbia, when different scenarios of the impacts of climate change are investigated.

90   The results obtained from the analytical analysis will be useful to evaluate future freshwater

91   availability and to plan future use of fresh groundwater resources in a sustainable manner.

92   The same methodology could be applied to any case of strip oceanic islands worldwide when

93   the assumptions for the application of the analytical methodology can be made.

94

2. Analytical methodology

96   Strip islands are elongated islands whose length is significantly greater than their width, with

97   a longitudinal axis of symmetry. The proposed methodology to assess the impacts of climate

98   change on groundwater resources in an oceanic strip-island unconfined aquifer is designed

99   to be conducted in five steps:

100   1. The first step consists of testing whether the simplified Dupuit-type analytical

101   groundwater flow model of the freshwater lens of the strip oceanic island can be

102   applied to the island that is being considered. For this, it must be verified that the

103   assumptions required by the Dupuit flow-type model are satisfied. Piezometric

104   observations on the island must be available in order to create a piezometric map and

105   to investigate if this map can be fitted to a Dupuit-type flow conceptual model of the

106   island.

107   2. When the Dupuit-type flow assumptions are verified, the equations developed by

108   Chesnaux (2016) can be used to calculate the change of the volume of the freshwater

109   lens with sea-level rise. Note that before conducting this calculation, the

110   hydrogeological parameters contained in the equation of Chesnaux (2016) must be

111   determined.

3. The effects of coastal erosion can be included in the Chesnaux (2016) equation in order to obtain a new equation that now combines the effects of sea-level rise and coastal erosion, to determine the global change in the volume of the freshwater lens with climate change.

4. The total loss of recharge of the island with climate change can be calculated from the loss of land due on sea-level rise and coastal erosion combined with the recharge rate that may also evolve with climate change. The predicted values of the loss of recharge can then be compared with the fresh groundwater uptake from the island residents in order to determine if the groundwater exploitation, depending on future scenarios of developments, will not exceed the renewal rate of groundwater resources in a context of climate change

5. Finally, a sensitivity analysis can be conducted on the results of both the changes of the volume of the freshwater lens and the change of total recharge of the lens considering different predicted scenarios of sea-level rise and coastal erosion, as well as recharge rates due on precipitation changes.

2.1 Dupuit-type groundwater flow model of the strip-island unconfined aquifer

The steady-state regional flow solution for strip oceanic islands is given in the framework of Dupuit's assumptions (Dupuit, 1863): the island aquifer is unconfined and saturated, homogeneous and isotropic with a hydraulic conductivity represented by a unique value K that is constant. This value can, however, represent an equivalent average value for a system of multi-layered aquifers. The equipotential surfaces are vertical and the velocity is uniform over the entire depth. In the case of oceanic islands, a freshwater lens floats on top of saltwater, such that the interface between the freshwater and saltwater is considered as an

136   impermeable boundary for freshwater. Also, the aquifer is considered to be uniformly

137   recharged and its discharge into the ocean is represented by a constant head boundary

138   condition. In this study, the closed-form solutions are developed for a constant value of the

139   rate of recharge; but in a context of climate change, recharge rates may also be subject to

140   changes. Lastly in terms of limiting assumptions, the transition zone between the freshwater

141   lens and the saltwater is not taken into account, assuming a sharp interface between

142   freshwater and saltwater.

143   One-dimensional equations for groundwater flow in oceanic islands have been addressed by

144   Fetter (1972). The problem is defined using coordinates (x, y), but the flow is considered

145   horizontal and one-dimensional according to the Dupuit approximation, and indicates that

146   the hydraulic head is dependent only on x. The vertical plane, defined by $x = 0$, represents

147   the axis of symmetry of the island and also represents the water divide (hydraulic gradient

148   is zero), since the down-gradient boundary is a hydraulic head that is the same on both sides

149   of the island. The length of the island is defined theoretically to be infinite; whereas its half

150   width is L (the total width of the island is $2L$). Due to the symmetry of the island, the problem

151   is solved between $x = 0$ to $x = L$ (Figure 1(a)).

152   Figure 1(b) describes the oceanic island system considered. The solution for the

153   elevation of the water table above sea-level, $h(x)$, is given by Fetter (1972), and is expressed

154   as follows:

155

156    $$h(x) = \sqrt{\frac{W}{K} \cdot \frac{\Delta\rho(L^2 - x^2)}{(\rho_f + \Delta\rho)}} \tag{1}$$

157

158   Where W is the recharge rate [LT^{-1}] of the aquifer, K its hydraulic conductivity [LT^{-1}], ρ_f is

159   the density of freshwater, ρ_s is the density of saltwater, and $\Delta\rho = \rho_s - \rho_f$. Note that the ocean

160   surface is taken as the datum for the heads $h(x)$. Equation (1) was obtained by Fetter by

161   combining Darcy's law and the Ghijben-Herzberg relation (Drabbe and Badon Ghijben,

162   1889; Herzberg, 1901), giving the position of the freshwater/saltwater interface. This latter

163   relation is written as follows (Equation (2)):

164

165    $$z(x) = \frac{\rho_f}{\rho_s - \rho_f} \cdot h(x) = \frac{\rho_f}{\Delta\rho} \cdot h(x) \qquad (2)$$

166

167   where $h(x)$ is the elevation of the water table above sea-level, and $z(x)$ is the depth to the

168   fresh-saline interface below sea-level.

169

170

171

172   **2.2 Freshwater lens volume of the strip island**

173   The volume of the freshwater lens of the strip oceanic island is given by Chesnaux (2016).

174   In the framework of this study, where climate change will affect the volume of the lens, let's

175   write V_t [L^2] to be the volume of the lens per unit length of the island at time t and L_t to be

176   the half-width of the island [L] at time t. The total volume of the freshwater lens per unit

177   length of the island at time t is written as follows (Equation (3)):

178

179    $$V_t = \frac{\pi n_e}{2} \sqrt{\frac{W}{K}\left(1 + \frac{\rho_f}{\Delta\rho}\right)} \cdot L_t^2 \qquad (3)$$

180

181 with n_e the effective porosity of the aquifer.

182 The volume of the lens will change with L_t and, in a context of climate change, L_t will

183 diminish with the effects of both sea-level rise and coastal erosion.

184

185 **2.3 Land-surface inundation: Sea-level rise and coastal erosion**

186 Sea-level rise and coastal erosion are parameters that must be predicted by climatic models.

187 The rates of sea-level rise and coastal erosion will be used to determine the change in the

188 strip island width, which is represented by the variation of L_t with time (Figure 1(b)).

189

190 *2.3.1 Sea-level rise*

191 Let's define S_t to be the sea-level at time t and ΔS_t to be the change of sea-level over time t:

192 $\Delta S_t = S_t - S_0$ with S_0 and S_t the initial sea-level and the final sea-level after time t, respectively.

193 If $\Delta S_t > 0$, sea-level has risen during t and conversely if $\Delta S_t < 0$, sea-level has dropped during

194 t. A change of S (ΔS_t) over time t will cause a change of L ($\Delta L_t = L_t - L_0$) over time t depending

195 on θ, the slope (angle of the shore face compared to the horizontal) of the island aquifer

196 (Equation (4)):

197

198 $$\frac{\Delta S_t}{\Delta L_t} = -\tan\theta \qquad (4)$$

199

200 The resulting inundation of the strip island in the case of sea-level rise ΔS_{SLR} during t is of

201 $\Delta L_{SLR} = -\Delta S / \tan\theta$ as ΔL_{SLR} is negative and ΔS positive.

202

203 *2.3.2 Coastal erosion*

204 While sea-level rise is usually considered to represent the main impact of climate change on

205 coastal aquifers, other impacts such as coastal erosion can also be expected. Coastal erosion

206 will diminish the width of islands and the erosion rate can be noted as ΔL_{CE}. This erosion

207 rate corresponds to the loss of coastal land (ΔL_{CE} is negative) during a given period of time.

208 Usually, erosion is expressed as a length of width of coast lost per year. This loss will cause

209 the progression of seawater into the land, having comparable effects of sea-level rise. Indeed,

210 both sea-level rise and erosion lead to land-surface inundation.

211

212 *2.3.3 Total land-surface inundation*

213 The total land-surface inundation, noted as ΔL (negative value), due to climate change

214 expresses the total loss of land due on the combination of sea-level rise (ΔL_{SLR}) and coastal

215 erosion (ΔL_{CE}). ΔL can therefore be expressed as (Equation (5)):

216

217 $\Delta L = \Delta L_{SLR} + \Delta L_{CE} = -\Delta S/tan\theta + \Delta L_{CE}$ (5)

218

219 **2.4 Changes in freshwater lens volume**

220 After there is a change of the width of the island with climate change over time t, the

221 consecutive change in the volume ΔV of the freshwater lens can be determined by using

222 Equation (3) to yield Equation (6):

223

224 $\Delta V = V_t - V_0 = \frac{\pi n_e}{2}\sqrt{\frac{W}{K}\left(1 + \frac{\rho_f}{\Delta\rho}\right)} \cdot \left(L_t^2 - L_0^2\right) = \frac{\pi n_e}{2}\sqrt{\frac{W}{K}\left(1 + \frac{\rho_f}{\Delta\rho}\right)} \cdot \Delta L \cdot (\Delta L + 2L_0)$ (6)

225

226   Combining Equations (5) and (6) gives an expression of the change of volume of the

227   freshwater lens (per unit length of the strip island) with sea-level rise and erosion (Equation

228   (7)):

229

230    $$\Delta V = \frac{\pi n_e}{2}\sqrt{\frac{W}{K}\left(1+\frac{\rho_f}{\Delta\rho}\right)} \cdot \left(\Delta L_{CE} - \frac{\Delta S}{tan\theta}\right) \cdot \left(\Delta L_{CE} - \frac{\Delta S}{tan\theta} + 2L_0\right)$$ (7)

231

232   Equation (7) is the closed-form solution for calculating the change of volume of the

233   freshwater lens in a strip oceanic island as a function of the initial half-width L_0 of the island

234   and the slope θ of the coast when sea-level rises by ΔS and when coastal erosion (loss of

235   width of the island) is ΔL_{CE}. Note that ΔV is per unit length of island and that its value is

236   negative.

237   Equation (7) depends on the recharge rate W that can also change over time with climate

238   change and it can be observed that the change of volume is directly proportional to the root

239   square of the rate of recharge.

240

241   **2.5 Groundwater total recharge**

242   Groundwater recharge rates W_t [LT^{-1}] may change with climate change over time t on the

243   one hand but on the other hand the total recharge, noted R_t, will diminish with climate change

244   due on the loss of land surface (land surface inundation). The total groundwater recharge of

245   the freshwater lens R_t [L^2] at time t during a period of time Δt per unit length of the strip

246   island corresponds to the recharge rate W during the period of time Δt multiplied by the

247   surface of the strip island of width $2L_t$ at time t per unit length of the island (Equation (8)):

248

249    $R_t = 2 \cdot L_t \cdot W_t \, \Delta t$ (8)

250

251   The value of the total recharge R_t during a period of time Δt indicates the amount of

252   freshwater that is renewed in the lens during Δt. This amount theoretically corresponds to

253   the amount of water that can be tapped in the lens without depleting the resource (the rate of

254   uptake should not exceed the rate of renewal). Consequently, characterizing the value of R_t

255   in a context of climate change is of crucial interest and importance for decision-makers since

256   it corresponds to the maximum value of fresh groundwater that can be exploited in the lens

257   during a period of time Δt.

258   R_t represents a threshold value when planning on future scenarios of possible water use when

259   one includes the effects of climate change on both land inundation and groundwater recharge

260   rates.

261

262   ## 3.   Illustration with a case study: example of Savary Island, Canada

263

264   **3.1 Description of Savary Island and its hydrogeological features**

265   Savary Island is a long and narrow oceanic island on the Pacific coast of British

266   Columbia, Canada, measuring approximatively 7.5 km long in an east-west direction and

267   0.6 to 0.8 km wide in a north-south direction. It can be considered as a strip island, with the

268   initial assumption that it satisfies the conditions for the application of the Dupuit

269   approximation on the freshwater lens of the island (this assumption will be verified in this

270   study, based on the results obtained from the interpolation of the water table elevations).

271   Savary Island is exposed to the consequences of climate change, including sea-level rise

272   combined with an intense erosion of its coast. For these reasons, Savary Island offers the

273   typical and representative conditions to illustrate the methodology proposed in this study, to

274   quantify the consequences of climate change for strip oceanic islands.

275   The mean shore slope of the island is 40 m/km. Savary Island is located 150 km

276   north-west of Vancouver and the island is populated with 100 permanent inhabitants whereas

277   it can be populated with 500 inhabitants during the summer season since it is very attractive

278   to tourism. The island relies on only its fresh groundwater lens for water supply (domestic

279   use only). Savary Island is composed mainly from sand (known as Quadra sand) deposited

280   by glaciers during the Pleistocene. This sand deposit forms an aquifer, for which the mean

281   hydraulic conductivity has been determined with a pumping test: average $K = 5 \times 10^{-5}$ m/s

282   (Thurber Engineering Ltd., 2003). Homogeneous and isotropic conditions can be considered

283   for this aquifer. The effective porosity n_e of the aquifer is 0.3. The island receives an average

284   of 1,100 mm precipitation per year from which 23% is recharge for the aquifer, making W

285   equal to 250 mm/year (Pacific Hydrology Consultants LTD., 1987). A groundwater well

286   database is available and contains information for 48 domestic wells (British Columbia

287   Government, 2020); the *British Columbia Water Resources Atlas* is a GIS based system that

288   provides aquifer maps and water well information (stratigraphy, static water levels and

289   specific capacity tests). Figure 2 shows a map of Savary Island with the digital elevation

290   model (DEM) based on LiDAR data and the locations of the domestic wells. Figure 2 shows

291   that the distribution of the domestic wells is not uniform, with most of the wells located in

292   the western and eastern parts of the island where urban development is found.

293

294

295

296   Regarding the scenarios of sea-level rise and coastal erosion, a constant rate of sea-level rise

297   of 0.7 mm/year (for the next 100 years) was selected as proposed by Forbes et al. (2004) and

298   a constant average rate of coastal erosion of 0.2 m/year, specifically for Savary Island, has

299   been considered according to Thurber Engineering Ltd. (2003).

300

301   **3.2 Results**

302   It is first verified that the Dupuit model can be applied to the groundwater system of Savary

303   Island based on the piezometric map of the freshwater lens of the island. Once the Dupuit

304   flow model is verified, the equations for assessing the impacts of climate change are then

305   applied to draw conclusions on the consequences of climate change for the next 100 years.

306

307   *3.2.1 Flow model: interpolated hydraulic heads in the aquifer of Savary Island*

308   The piezometric data at the 48 wells are included in the well database used to create the

309   piezometric map of Savary Island (Figure 3). Water levels $h(x)$ corresponding to elevation

310   of the water table above sea level are interpolated considering a quadratic relationship of the

311   squared hydraulic heads and the spatial distance according to Equation (1) when the Dupuit

312   assumptions are considered for the flow model. Note that the application of the Dupuit

313   assumption is later verified with the constant parameters of the regression equation obtained

314   from the interpolation. Figure 3 shows the interpolated water table position map (or

315   piezometric map) of the Savary Island freshwater lens aquifer. Interpolation was realized

316   using the ArcGIS software. Note that the piezometric map was generated only for the

317   western part of the island, where there were sufficient observation wells (used to constrain

318   the interpolation of the water levels) with a satisfying density and distribution (see Figure 2)

319   to apply the interpolation of the piezometric observations in the wells.

320

321

322

323 The interpolated water-table-elevation profile $h(x)$ obtained along cross section A-A' of

324 Figure 3 is shown in Figure 4. The freshwater lens thickness, which equals $h(x) + z(x)$, is

325 calculated from Equation 2 with the $h(x)$ interpolated values and is represented in Figure 4.

326 Note that the cross section A-A' has a length (equal to $2L$) of 660 m (L=330 m).

327

328

329

330 By plotting the squared water table elevation (h^2) as a function of x (along cross section A-

331 A' with x=0 centered on A-A'), a second degree polynomial relationship is obtained since a

332 quadratic interpolation was applied to generate the water table elevation map satisfying the

333 Dupuit-Forchheimer theory (Equation 1). After applying the quadratic regression to h^2 vs. x,

334 the resulting equation is written as: $h^2 = -5\times10^{-6}x^2 + 0.53$ with h and x expressed in meters

335 (Figure 5).

336

337

338

339 Therefore, the constant $(\Delta\rho \times W/K)/(\rho+\Delta\rho)$ in Equation 1 equals 5×10^{-6}. With ρ (density of

340 freshwater) equal to 1 and $\Delta\rho$ equal to 0.25, it follows that W/K is equal to 2×10^{-4}. Comparing

341 this value obtained from applying the Dupuit model of the freshwater lens of Savary Island

342 with the observed value of W/K allows one to evaluate the validity of applying the Dupuit

343 model for Savary Island. With a recharge value of 250 mm/y (i.e. 8×10^{-9} m/s) and a hydraulic

344 conductivity value of 5x10^{-5} m/s, it follows that W/K is equal to 1.6×10^{-4}. This value is very

345 close to the value of 2×10^{-4} obtained from the Dupuit model. Such a small difference shows

346 that the hydrogeological conditions on Savary Island allow the application of the Dupuit

347 model from which the analytical solutions for assessing the consequences of climate change

348 can be determined as presented earlier.

349

350 *3.2.2 Impacts of climate change: variations of the volume of the freshwater lens and of the*

351 *total recharge*

352 The future impacts of climate change on the groundwater resources in Savary Island are

353 calculated with Equations (7) and (8) taking into account the cumulative effects of sea-level

354 rise and coastal erosion. Table 1 summarizes the parameters and the mean values that are

355 considered to solve the equations in the specific case of Savary Island.

356

357 Table 1. Input parameters considered for the case of Savary Island.

Parameter	Value
L_0 (Initial average half-width of Savary Island, m)	330
Total length of Savary Island (m)	7,500
Average shore slope (m/km)	40
Tanθ	0.04
Hydraulic conductivity K (m/s)	5×10^{-5}
Annual recharge rate W (mm/y)	250
Effective porosity n_e	0.3
Mean annual sea-level rise (ΔS per year, m/y)	0.007

Mean coastal erosion rate (ΔL_{CE} per year, m/y)	0.2

358

359   The initial total volume (present volume at initial time) of the freshwater lens is calculated

360   by $V_0 = \frac{\pi n_e}{2} \sqrt{\frac{W}{K}\left(1 + \frac{\rho_f}{\Delta\rho}\right)} \cdot \left(L_0^2\right) \cdot 7{,}500$ and is equal to ~ 31 million m³.

361   The changes in the total freshwater lens volume ΔV are calculated for the next 100 years

362   from an annual basis using Equation (7). The results are presented in Figure 6 where the

363   effects of sea-level rise on the one hand and the effects of coastal erosion on the other hand

364   can be visualized.

365

366

367

368   In the example presented in Figure 6, the respective effects of sea-level rise and coastal

369   erosion on the decrease of the volume of the freshwater lens are comparable, with coastal

370   erosion having an effect slightly greater than sea-level rise. In total, after 100 years, it can

371   be observed that the freshwater lens volume will have diminished by more than 22% due to

372   climate change (freshwater lens volume to be $\sim$24.4 million m³ in 2120 whereas it is $\sim$31

373   million m³ in 2020). Note that the recharge rate has been considered to be fixed at $W = 250$

374   mm/y but this rate may also evolve with climate change and the calculations conducted with

375   Equation (7) could be conducted accordingly when considering variable values of W. This

376   is the same for the rates of sea-level rise and coastal erosion that have been taken to be

377   constant for the next century; these rates could evolve over time and could be changed

378   accordingly. A further sensitivity analysis could be conducted from Equation (7) when

379   changing the values of the different parameters.

380   A last analysis of the impacts of climate change on Savary Island's groundwater resources

381   consists of assessing the renewable volumes of the total groundwater recharge in the island,

382   to be calculated from Equation (8). This total recharge to be defined over a period of time

383   defines the amount of freshwater that could potentially be extracted without depleting the

384   freshwater lens. The total recharge over a period of time, expressed in Equation (8), defines

385   the total flux of infiltrated freshwater flowing through the lens, from recharge with rainwater

386   to discharge to the ocean. Today, the total recharge for year 2020 calculated from Equation

387   (8) is 1.24 million m^3 with L_0 = 330 m. Considering that 100 inhabitants currently live

388   permanently on Savary Island and that they consume ~350 L per day and per inhabitant, the

389   total amount of freshwater tapped each year in the freshwater lens is ~13,000 m^3. This

390   volume of consumed freshwater consequently corresponds to ~1% of the renewable annual

391   rate of freshwater of the island. This value of 1% is low but it should be reminded that this

392   is a minimal rate because the population of the island can increase to several hundreds when

393   including the visitors during the summer season. In 100 years, with the predicted effects of

394   climate change using Equation (5), that considers both effects of sea-level rise and coastal

395   erosion, the land-surface inundation is calculated to be 37.5 m, from which 17.5 m of land

396   loss will be due on sea-level rise and 20 m of land loss will be due to erosion. The new mean

397   value of half-width of the island after 100 years, $L_{100y,}$ will therefore be 292.5 m. Applying

398   Equation (8) to this new value of L yields a total annual recharge of 1.1 million m^3 for year

399   2120 if the recharge rate W is considered unchanged. This new value of total recharge is to

400   be compared with the value of 1.24 million m^3 for today, in 2020, and shows a decrease of

401   more than 11% of the groundwater transiting in the lens. If the population is unchanged in

402   100 years (still 100 inhabitants on Savary Island), then the water consumption will

403   correspond to a new value of 1.16% of the renewable annual rate of freshwater of the island

404   in 2120, ie an increase of 0.16% on the previous rate of 2020.

405

4. Discussion and conclusion

407   The proposed methodology to assess the impacts of climate change in the strip oceanic island

408   of Savary Island could be extended to any strip oceanic island worldwide when it can be

409   verified that Dupuit flow assumptions apply to groundwater flow in the freshwater lens.

410   From the proposed equations and considering Dupuit assumptions, both the effects of

411   climate change on sea-level rise and coastal erosion can be evaluated on the change of

412   volume of the freshwater lens on the one hand and on the change of total recharge in the

413   island on the other hand. Considering the uncertainties that exist both on the hydrogeological

414   parameters of the island and on the predicted scenarios of climate change, sensitivity analysis

415   can be conducted from the proposed equations to determine different possible scenarios as a

416   function of the values of the parameters involved in the predictions. The accuracy of the

417   predictions not only depends on the accuracy of the climate prediction models, but also on

418   the accuracy of the hydrogeological model. The results obtained for the impacts on fresh

419   groundwater resources strongly depend on the strength and reliability of the climate models.

420   The uncertainties relating to coastal erosion values represent a limitation of the predicting

421   model. Indeed, a uniform sea-level rise may lead to a non-uniform coastal erosion of the

422   shore; for this reason, considering a mean coastal erosion rate may be a limiting assumption.

423   It should be noted that the rate of recharge may vary with climate change. This variation

424   should be predicted and taken into account in the equations, in addition to sea-level rise and

425   coastal erosion, when assessing the impacts of climate change on fresh groundwater

426   resources.

427   The protection of the shore against coastal erosion could lower the impacts of climate change

428   on inland inundation. Land reclamation could also be considered to reduce the impacts of

429   sea-level rise and coastal erosion, since the reclamation mitigates the effects of loss of land

430   due to erosion and coastal inundation.

431   The proposed equations may prove to be useful to not only predict how island fresh

432   groundwater resources will deplete with climate change but also to manage future

433   groundwater use in regards to available resources in a context of increase of coastal and

434   island populations. Although the proposed model requires one to consider assumptions that

435   simplify the reality, it remains that the proposed equation can still give a first estimate of the

436   impacts of climate change. Finally, the advantage of using a simplified model and simple

437   closed-form analytical solutions is that practitioners and decision makers can easily include

438   the solutions in their toolbox with very limited costs.

439

5. Acknowledgements

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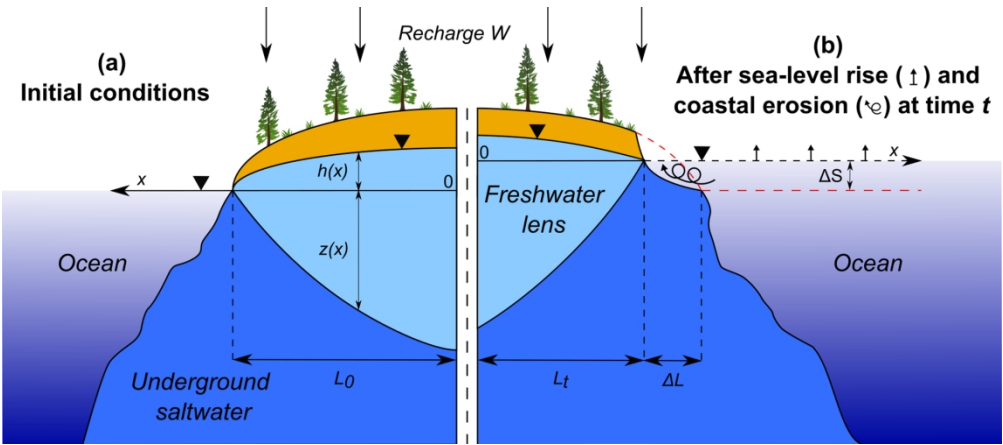513

514

515   FIGURE CAPTIONS:

516

517   Figure 1 (a): Cross-section of the hydrogeological conceptual model in a strip-island

518   unconfined aquifer (left hand side) and (b) Effects of sea-level rise and coastal erosion (right

519   hand side).

520

521   Figure 2: Location of Savary Island, digital elevation model (DEM) and locations of the

522   domestic wells.

523

524   Figure 3: Interpolated observed water-table elevations in the western part of Savary Island.

525   The water-table elevations are expressed in meters above sea level.

526

527   Figure 4: Digital elevation model (DEM), water table profile and saltwater/freshwater

528   transition zone modeled along the cross section A-A' according to the Dupuit model.

529

530   Figure 5: Interpolated squared saturated thickness (h^2) along cross section A-A' in Savary

531   Island.

532

533   Figure 6: Prediction of the variation of volume of the freshwater lens of Savary Island with

534   sea-level rise and coastal erosion for the next 100 years.

535

536

Figure 1 (a): Cross-section of the hydrogeological conceptual model in a strip-island unconfined aquifer (left hand side) and (b) Effects of sea-level rise and coastal erosion (right hand side).

Figure 2: Location of Savary Island, digital elevation model (DEM) and locations of the domestic wells.
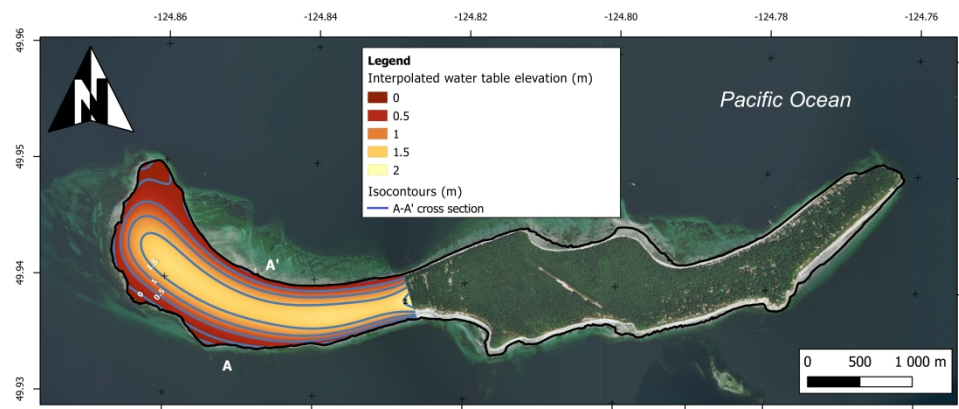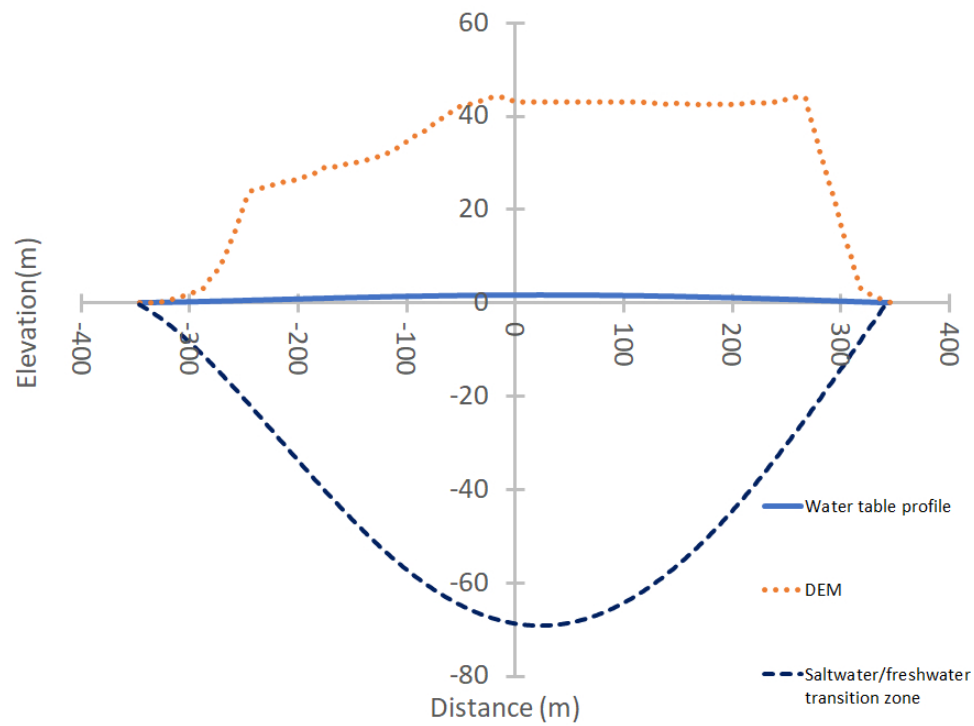
825x583mm (72 x 72 DPI)

Figure 3: Interpolated observed water-table elevations in the western part of Savary Island. The water-table elevations are expressed in meters above sea level

Figure 4: Digital elevation model (DEM), water table profile and saltwater/freshwater transition zone modeled along the cross section A-A' according to the Dupuit model.
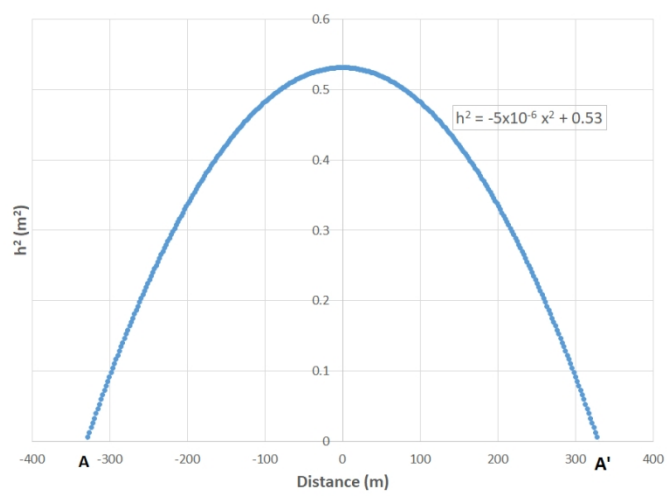
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Figure 5: Interpolated squared saturated thickness (h2) along cross section A-A' in Savary Island.
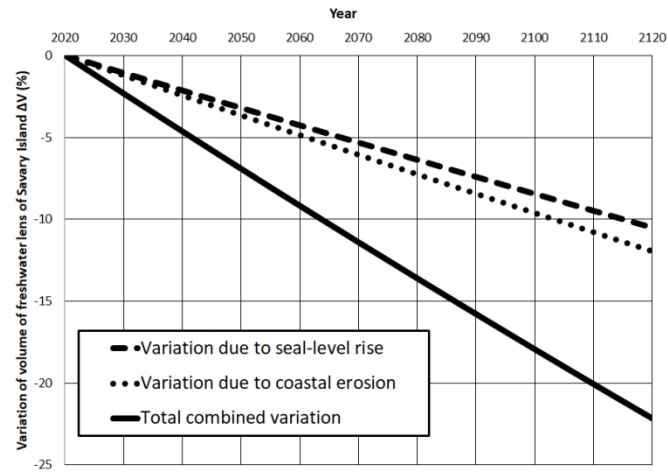
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Figure 6: Prediction of the variation of volume of the freshwater lens of Savary Island with sea-level rise and coastal erosion for the next 100 years.

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