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1 **Hydrological effects on gravity and correlations between gravitational**
2 **variations and level of the Alzette River at the station of Walferdange,**
3 **Luxembourg**

4
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6 **Faculty of Science, Technology and Communication. University of Luxembourg**

7
8 **Abstract**

9 *The gravitational effects of water storage variations driven by local precipitation*
10 *events are modeled for the Walferdange Underground Laboratory for Geodynamics*
11 *(WULG) in the Grand Duchy of Luxembourg. A modified mass continuity model is*
12 *implemented, which uses rainfall data from Walferdange as input. In the absence of soil*
13 *moisture and groundwater level information, the model is empirically parameterized.*
14 *Model outputs are compared to the gravity time series registered with the Observatory*
15 *Superconducting Gravimeter CT040 located in the WULG. We find that the model*
16 *explains 77% of the gravity residuals. In addition, a statistical analysis is carried out to*
17 *determine the relationship between precipitation, gravity variations and water level*
18 *changes in the nearby Alzette River. A time delay of 88 ± 34 min between the maximum*
19 *variation rates of the water level and gravity signal has been calculated. The signals*
20 *have an admittance of 45 ± 5 cm μGal^{-1} .*

21

22 **Keywords:** Gravity and Superconducting gravimeter, Hydrology, Groundwater,
23 Precipitation

24

25 **1. Introduction**

26 The effect of water storage variations on gravity has become an important issue for
27 improving the investigation of gravity measurements. Specifically, local water storage
28 variations within 10 km of a station alter the local mass field and thus can significantly
29 affect gravity observations [Van Camp *et al.*, 2006]. Various authors have analyzed the
30 effects of parameters such as local precipitation, soil moisture and groundwater storage
31 on gravity observations [e.g. Meurers *et al.*, 2007; Van Camp *et al.*, 2006; Kroner and
32 Jahr, 2006; Bower and Courtier, 1998; Boy and Hinderer, 2006; Kroner, 2001; Peter *et al.*,
33 1995; Harnish and Harnish, 2002; Crossley and Xu, 1998; Imanishi *et al.*, 2004;
34 Llubes *et al.*, 2004; Delcourt-Honorez, 1989]. Other authors [van Dam *et al.*, 2001;
35 Crossley *et al.*, 2005; Hinderer *et al.*, 2006; Naujoks *et al.* 2007] have investigated the
36 consequences of longer wavelength (several 100 km) water storage components on the
37 gravity signal. At these wavelengths, the displacement of the Earth's surface due to the
38 excess mass is also important.

39 The response of local gravity to local changes in water storage is site dependent
40 [Hokkanen *et al.* 2005]. Techniques and schemes for mitigating the signal in gravity data
41 at one location are usually not entirely applicable to another location. In this study, we
42 look at the physical relationship between water storage variations driven by local
43 precipitation events and local gravity changes at Walferdange, in the Grand Duchy of
44 Luxembourg. For the gravity observations, we use the data collected by the
45 superconducting gravimeter CT040 (SG) located in the Walferdange Underground
46 Laboratory for Geodynamics (WULG).

47 The present paper builds on the results of previous authors who have also investigated
48 the correspondence between gravity and local water storage variations. A new and simple
49 scheme is provided to remove the effects of precipitation events in the gravity
50 observations. A synthesis of the different approaches that can be found in recent literature
51 is proposed. The model is then extended to the Walferdange case by including a new
52 parameter to take into account the seasonal variability of groundwater behavior.

53 An empirical model is developed, based on a modification of the basic mass continuity
54 model, to estimate water storage variations due to local precipitation [*Meurers et al.*,
55 2007]. This model is used to correct the gravity time series residuals of the
56 superconducting gravimeter. A statistical analysis is then undertaken to determine the
57 correlation between gravity variations registered by the SG and water level changes in the
58 nearby Alzette River.

59 In Sections 2 and 3, a synthetic description of the hydrological recharge and discharge
60 processes related to the water cycle is given. Here the hypotheses leading to a tank model
61 representation are described. In order to underline the dependence of the model
62 parameters on hydrological parameters, such as porosity and hydraulic conductivity, as
63 indicated by *Van Camp et al.* [2006], the steps leading to the fundamental model
64 equations are detailed. This is achieved by combining the mass continuity equation and
65 Darcy's law [*Fetter*, 2001; *Roche*, 1963], which describes the flow of a fluid through a
66 porous medium.

67 In Section 4, modeled gravity variations are estimated using an admittance factor
68 between the gravity change and the precipitation height. This is done by decomposing the
69 area above the gravimeter in a discrete number of prismatic elements (the precipitation

70 height corresponding to the element thickness). The gravity effect on the SG is calculated
71 using Newton's law of universal attraction. A further hypothesis is developed, regarding
72 the seasonal variability of a model parameter, which represents the gravity recovery rate
73 after a rainfall and its physical significance is discussed.

74 In Section 5, the model outputs for a set of empirically evaluated parameters are
75 presented and discussed.

76 In Section 6, a statistical analysis is presented to determine the correlation between the
77 gravity signal variations registered by the SG and the water level of the Alzette River.
78 The gravity variation due to the precipitation should appear before the change in river
79 level. The gravity observation should also contain information on the degree of soil
80 saturation. Understanding the relationship and temporal dependence between the
81 observed precipitation and the gravity changes might improve our ability to predict of
82 extreme events like flooding. We estimate the mean time delay between the maximum
83 variation of the gravity signal and the Alzette water level as a function of a set of sampled
84 showers. Finally, the correlation between the gravity variation and water level variation is
85 calculated and discussed.

86

87 **2. Hydrological recharge and discharge processes**

88 Variations in the amount of water stored in the ground exert an effect on the gravity
89 signal through essentially two different mechanisms: 1) the Newtonian attraction exerted
90 by the water mass and 2) the ground deformation resulting from the water load and the
91 associated mass redistribution. The effect of the ground deformation on gravity is a long
92 wavelength effect (> 50 km).

93 Groundwater flow is possible because Earth materials are usually not impermeable,
94 but characterized by the presence of voids (pores) included in a solid matrix. The
95 groundwater and soil moisture occur in the voids [Fetter, 2001]. For a control volume V_t
96 of a given material, the porosity P is defined as the ratio between the volume V_v of the
97 voids and the control volume V_t :

$$99 \quad P = \frac{V_v}{V_t} \quad (1)$$

100

101 If the voids are completely/partially filled with water, the medium is defined as
102 saturated/unsaturated.

103 The mechanical energy per unit weight possessed by a fluid is given by Bernoulli's
104 law:

105

$$106 \quad h = \frac{v^2}{2 \cdot g} + z + \frac{p}{\rho \cdot g} \quad (2)$$

107

108 where v is the fluid velocity, g is the gravity acceleration, z is the elevation of the fluid
109 center of mass with respect to a reference level, p is the pressure, ρ is the fluid density
110 and h , expressed in units of length, is defined as the hydraulic head. The kinetic term
111 $v^2/2g$ is generally negligible in problems related to groundwater flow [Fetter, 2001].

112 The flow through a porous medium is described by Darcy's law:

113

$$114 \quad q = K \cdot \left(\frac{dh}{dl}\right) \quad (3)$$

115

116 where q (length/time) is the flow per surface unit or specific flow, h is the hydraulic head.
117 and l is the displacement in the flow direction. The proportionality coefficient (K)
118 between the specific flow and the hydraulic gradient (dh/dl) quantifies the capacity of
119 fluids to move through porous media. The coefficient is known as the hydraulic
120 conductivity or permeability coefficient. It is important to underline that hydraulic
121 conductivity is a function of the characteristics of both the fluid and the porous medium
122 [Fetter, 2001]. The general formulation of problems related to groundwater flow is based
123 on a combination of Darcy's law and continuity equations with reference to control
124 volumes [Anderson, 2007].

125 For unconfined aquifers the water table represents the interface between the saturated
126 zone (below) and the unsaturated zone (above) [Milly and Shmakin, 2002]. The water
127 volume contained in the saturated zone represents the groundwater reservoir. When
128 precipitation occurs, part of the fallen volume of water is retained by the vegetation
129 canopy or human artifacts, another part is subject to direct surface runoff or other
130 subsurface flow, and one part infiltrates through the unsaturated zone to increase the
131 groundwater reservoir storage. This infiltration represents the recharge process, with
132 augmentation of the water storage. After the precipitation event and the recharge process,
133 the stored water will decrease through different mechanisms, such as evaporation and
134 evapotranspiration from the unsaturated zone or efflux through filtration from the
135 saturated zone, to reach draining flows. This represents the discharge process, with
136 consequent diminution of the water storage. In conclusion, both the recharge and the

137 discharge must be seen as the superposition of different processes with different
138 characteristic time scales. The number of parameters needed to describe those processes
139 is very high, and are subject to strong time and space variability. Different models have
140 been proposed to analyze the complex processes related to water (and energy) storage
141 [Manabe, 1969; Milly and Shmakin, 2002, Iffly et al., 2004]. In the absence of direct
142 information about soil moisture and groundwater level, the development of an empirical
143 local model is required to describe the water storage variations. Important simplifications
144 of the processes involved are necessary.

145

146 **3. The Tank Model**

147 The fraction of precipitation that infiltrates the soil, percolates vertically through the
148 unsaturated zone to reach the saturated zone below the water table. This process
149 increases the groundwater reservoir storage. In the case of unconfined aquifers (presence
150 of one impermeable underlying layer), the efflux from the saturated zone can essentially
151 be described as horizontal filtration through a porous medium. The tank model [Roche,
152 1963] represents a strong simplification: the discharge process is reduced to the efflux of
153 water contained in a tank (and not distributed in a solid matrix) through a porous plug. A
154 simple illustration of the tank model is given in Figure 1.

155

156 **Figure 1**

157

158 The relation between the flux from the porous plug and the hydraulic head is
159 expressed by Darcy's law (Eq. (3)) in the following form [Roche, 1963]:

160

$$161 \quad Q = K \cdot \frac{s}{L} \cdot h \quad (4)$$

162

163 where Q represents the outgoing flux (volume/time), h is the water height (corresponding
 164 to the hydraulic head), s and L are the cross section and length of the plug, respectively
 165 (Figure 1). The parameters of the model have to be determined empirically. The outgoing
 166 flux is related to the water level through the hydraulic conductivity, which depends both
 167 on hydrological soil parameters, such as the medium's porosity, and on fluid
 168 characteristics such as viscosity. A hydrological volume balance is calculated, with
 169 reference to the elementary time interval dt:

170

$$171 \quad S \cdot dh(t) = -Q(t) \cdot dt + S \cdot r(t) \cdot dt \quad (5)$$

172

173 where r(t) represents the rainfall rate (length/time) and S the tank surface. Defining the
 174 level decrease rate, c (1/time), by:

175

$$176 \quad c = \frac{K \cdot s}{S \cdot L} \quad (6)$$

177

178 Substituting the definition of Q (Eq. (4)) into Eq. (5), the differential equation describing
 179 the water level variation becomes:

180

$$181 \quad \frac{dh(t)}{dt} = -c \cdot h(t) + r(t) \quad (7)$$

182

183 Equation (7) relates the water level, corresponding to the hydraulic head in this
 184 simplified representation, to the rainfall. In this equation, $r(t)$ is not a continuous function
 185 of time and the integration has to be performed numerically. In absence of precipitation,
 186 the equation can be analytically integrated leading to an exponential decay expression
 187 describing the draining of a tank through a porous plug.

188

189 **4. Relation between precipitation height and gravity variation**

190 The WULG is located underground in a derelict gypsum mine, at latitude 40.6700°N ,
 191 longitude 6.1500°E . The laboratory housing the Observatory Superconducting
 192 Gravimeter *CT040* lies at the end of an 800 m long tunnel cut into the side of a ridge.
 193 The gravity sensor is 295 m above sea level and about 80 m below the local surface. The
 194 area above the gravimeter has significant topographic slope gradients (See Figure 2), and
 195 is covered by uneven vegetation. The closest human artifacts (i.e. roads and buildings)
 196 are located at about 500 m from the gravimeter. All of these factors contribute to making
 197 the WULG seismically quiet.

198 In order to express Eq.(7) in terms of gravity variations, we estimate the admittance
 199 between the gravity change and the precipitation height. The gravity effect of a weathered
 200 area can be calculated using digital elevation models (DEM): the weathered ground layer
 201 is discretized in prismatic elements [*Van Camp et al., 2006; Banerjee and Das Gupta,*
 202 *1977; Talwani, 1973*]. The gravity effect Δg_e of a single element is given by:

203

$$204 \quad \Delta g_e = G \cdot \rho_{wet} \cdot \int_{x_1}^{x_2} \int_{y_1}^{y_2} \int_{z_1}^{z_2} \frac{z}{(x^2 + y^2 + z^2)^{3/2}} \cdot dx \cdot dy \cdot dz \quad (8)$$

205

206 where G is the Newtonian universal constant of gravity ($6.67428 \cdot 10^{-11} \text{ m}^3 \text{ kg}^{-1} \text{ s}^{-2}$) and
 207 ρ_{wet} is the density of the wet component of the weathered zone (mass/volume). The
 208 integration is carried out over the prism volume, delimited by the coordinates (x_1, y_1, z_1)
 209 and (x_2, y_2, z_2) in a Cartesian frame centered at the gravity station.

210 In absence of accurate information about ρ_{wet} in the weathered zone above the
 211 WULG, the calculation is made directly on prismatic water elements having the
 212 precipitation height as thickness. This simplification is adopted because the thickness of
 213 the weathered zone appears to be significantly smaller than the distance between the
 214 gravity sensor and the surface.

215 The 2000 m x 2000 m zone above the gravimeter is divided into 10000 prismatic
 216 elements of size 20 m x 20 m. The map projection of the discretized layer defines a 100
 217 x 100 grid. The square elements of the grid are identified by the indices i and j
 218 corresponding to the coordinates in meters $x_i=20i$, $y_j=20j$ and elevation z_{ij} in a local
 219 Cartesian frame (the coordinates are referred to the element central points). The
 220 gravimeter is located at (x_g, y_g, z_g) . The gravity effect Δg_{ij} of each prism (m s^{-2}) at the
 221 gravimeter location is calculated with:

222

$$223 \quad \Delta g_{ij} = G \cdot \Delta S \cdot \rho \cdot l_e \cdot \frac{z_{ij}}{((x_i - x_g)^2 + (y_j - y_g)^2 + (z_{ij} - z_g)^2)^{3/2}} \quad (9)$$

224

225 where ΔS is the surface area of the element (400 m^2), ρ represents the water density
 226 (1000 kg m^{-3}) and l_e is the element thickness (m). The total gravity effect Δg of the layer
 227 (m s^{-2}) on the gravity sensor is given by:

228

$$229 \quad \Delta g = \sum_{i=1}^{100} \sum_{j=1}^{100} G \cdot \Delta S \cdot \rho \cdot l_e \cdot \frac{z_{ij}}{((x_i - x_g)^2 + (y_j - y_g)^2 + (z_{ij} - z_g)^2)^{3/2}} \quad (10)$$

230

231 The admittance, α , between a gravity change (μGal) and a precipitation height (m) is
 232 directly calculated with Eq.(10), by defining $l_e=1$ m and expressing the gravity in μGal .
 233 The result is $\alpha=36 \mu\text{Gal m}^{-1}$. For reference, the value given by the Bouguer infinite plate
 234 model is $42 \mu\text{Gal m}^{-1}$. This value is generally adopted for almost flat surfaces. The
 235 significant height differences of the area above the WULG justify the calculation made
 236 on the actual topography.

237

238 **Figure 2**

239

240

241 With the calculation of the admittance between the hydrological component of the
 242 gravity variation and the precipitation height, the equation describing the gravity changes
 243 can be obtained by writing the continuity equation (7) in terms of gravity. This is done by
 244 multiplying both sides of Eq.(7) by α , setting $\Delta g=\alpha \cdot h$, $c=\gamma$, and changing the sign of the
 245 term $\alpha \cdot r$. This last step is required by the fact that the gravimeter is located in an
 246 underground laboratory: an increase of the stored water level above the gravimeter will
 247 produce a reduction of the gravity signal. We thus obtain:

248

$$249 \quad \frac{d(\Delta g)}{dt} = -\gamma(t) \cdot \Delta g - \alpha \cdot r(t) \quad (11)$$

250

251 where Δg represents the hydrological part of the gravity variation and γ (corresponding
 252 to c in Eq.(7)) is here defined as the gravity recovery rate after rainfall (1/time). The
 253 coefficient γ is related to hydrological parameters like hydraulic conductivity and
 254 porosity, in addition to the geometrical parameters depending on the local configuration.
 255 The inverse of γ , defined as τ , has the dimensions of a time and it characterizes the
 256 duration of the discharge phase. Equation (11) has been previously implemented by
 257 *Imanishi et al.* [2004] to calculate the gravity effects of underground water in Matsushiro
 258 (Japan). The basic tank model is modified using the hypothesis of a seasonal variability
 259 for the parameter γ . The seasonality is included to account for the annual changes in the
 260 meteorological and hydro geological conditions (i.e. evapotranspiration and hydraulic
 261 conductivity). This variability is expressed in the form:

$$263 \quad \gamma(t) = \gamma_0 \cdot (1 + A \cdot \cos(\frac{2 \cdot \pi}{T} \cdot t + \varphi)) \quad (12)$$

264
 265 where γ_0 is the mean value of γ in the period T (one year). The values of A (amplitude)
 266 and φ (phase) are evaluated empirically (see Section 5.2.). Finally, the equation for the
 267 gravity variation becomes:

$$269 \quad \frac{d(\Delta g)}{dt} = -\gamma_0 \cdot (1 + A \cdot \cos(\frac{2 \cdot \pi}{T} \cdot t + \varphi)) \cdot \Delta g - \alpha \cdot r(t) \quad (13)$$

270
 271 As already pointed out, the rainfall rate $r(t)$ is not defined by a continuous function of
 272 time but by a discrete set of values. To allow us to solve the equation using finite

273 difference algorithms, Eq. (13) has to be rewritten as a discrete expression. We define
 274 the terms of a progression:

275

$$276 \quad \Delta g(i+1) = (1 - \gamma(i)) \cdot \Delta g(i) - \alpha \cdot r(i) \quad (14)$$

277

278 where i represents the non dimensional time indices, $\gamma(i)$ is the non dimensional recovery
 279 rate and $r(i)$ are the precipitation heights. The time variable t in Eq. (13) is given by
 280 $t = \Delta t \cdot i$, where Δt is the reference time interval (1 hour in the hourly implementation), and
 281 the recovery rate function $\gamma(i)$ is formally identical to $\gamma(t)$.

282

283 **5. Data and Results**

284 **5.1. Input Data**

285 The available data for the model implementation are the local rainfall time series from
 286 the 1 January 2003 to the 1 January 2009. Two different data sources were available: the
 287 pluviometer of the Walferdange Meteorological Station and the WULG pluviometer
 288 (Figure 2). Both the pluviometers provide the rainfall heights (mm) at one-minute
 289 sampling intervals. A comparison between the two series indicates a qualitative
 290 similarity. A significant quantitative difference exists as well. The cumulative
 291 precipitation provided by the WULG is approximately 10% greater than the cumulative
 292 precipitation provided by the Walferdange Meteorological Station. This difference will
 293 be used to assess the uncertainties of the rainfall data. The time series provided by the
 294 WULG is displayed in Figure (3).

295

296 **Figure 3**

297

298 **5. 2. Model parameterization for the hourly implementation**

299 The value of the admittance, $\alpha=36 \mu\text{Gal m}^{-1}$ derived in Section 4, has been used for
300 the model parameterization in Eq.(13). The parameters γ_0 , A and φ in the same equation
301 are obtained empirically by a least square adjustment. The gravity variations observed
302 with the SG are compared with the values predicted by Eq.(13) using the rainfall data, for
303 the period 19 December 2003 to 1 December 2004. The parameters are determined from
304 the data in order to minimize the residuals. The values of $A=0.6$, $\varphi= 2\pi/5$, and
305 $\gamma_0=0.0011 \text{ hours}^{-1}$ provide the best results. For reference, *Meurers* (2007) adopted the
306 value $\tau=720$ hours for the discharge time parameter at the gravity station in Vienna,
307 which corresponds to $\gamma_0=0.0015 \text{ hours}^{-1}$ (see Section 4).

308

309 **5. 3. Results**

310 The rainfall time series provided by the WULG, integrated to hourly values and
311 referred to the mid-hour points, are used as model input. The rainfall heights are
312 expressed in meters. An uncertainty of 10% on the rainfall data, as determined by the
313 quantitative difference in the rainfall data from two closely space pluviometers (see
314 Section 5.1) is assigned.

315 The modeled hourly time series of the gravity (μGal) is compared with the observed
316 hourly time series obtained from the SG for the period 19 December 2003 to 1 January
317 2009. The instrumental drift of the SG is modeled using an exponential function [*Van*

318 *Camp and Francis, 2006*]. The modeled gravity (green), the observed gravity (blue) and
319 their difference (red), expressed in μGal , are displayed in Figure 4.a.

320

321 **Figure 4**

322

323 The RMS of the uncorrected gravity time series is $1.89 \mu\text{Gal}$. After removing the
324 modeled hydrological effects from the observations, an RMS value of $0.89 \mu\text{Gal}$ is
325 obtained, which corresponds to a 77% signal reduction.

326 The gravity changes after a high intensity precipitation event (Figure 4.b) show that the
327 gravity recovery process has a significantly longer duration than the gravity decrease
328 process. The tank model describes only the recovery process. The gravity decrease
329 process is considered as instantaneous. When a precipitation occurs, the rainfall height is
330 simply added to the current water level, producing an instantaneous gravity change. A
331 higher time sampling of the data is therefore not necessary.

332

333 **5. 4. Discussion**

334

335 The model provides a reasonable description of the medium and long term effects of
336 rainfall on the gravity observations. However, it does not describe short time scale
337 effects like air pressure changes or air mass redistribution which may themselves be
338 related to the precipitation events [*Meurers, 2007; Meurers et al., 2007*]. The hypothesis
339 of the seasonal variability of the gravity recovery rate after rainfall provides a better fit to
340 the actual gravity changes. This variability could be explained from four different factors.

341 First, it could be due to variability of the hydraulic conductivity K , which is related to
342 the parameter γ [Van Camp *et al.*, 2006]. K can be expressed in the form $K=k\cdot\rho\cdot g\cdot\mu^{-1}$,
343 where k (length²) is the permeability of the solid matrix, which depends only on the
344 characteristics of the porous medium. The term $\rho\cdot g\cdot\mu^{-1}$ depends only on the fluid
345 characteristics, where ρ and μ represent the density and the viscosity of the fluid,
346 respectively. The viscosity depends on groundwater temperature. At mid-latitude
347 locations such as Walferdange, groundwater temperature has a definite seasonal
348 variability, even if it is less sensitive in the saturated zone. *Bartolino* (2003) investigated
349 the annual groundwater temperature fluctuations as a function of depth below the surface
350 beneath the Rio Grande in New Mexico. He estimated an annual groundwater
351 temperature range varying from 22°C at 1 m depth below the surface to 4°C at 15 m
352 depth below the surface..

353 A second seasonal effect which could positively affect our comparison, could be due
354 to the infiltration variability. The runoff coefficients, and consequently the fraction of
355 precipitation infiltrating the soil, can have a significant seasonal variability, related to the
356 degree of saturation of the root zone.

357 Thirdly, the improvement could be due to evapotranspiration variability [*Hupet and*
358 *Vanclouster*, 2005]. The process of evapotranspiration has a strong dependence on air and
359 soil surface temperatures that are subjected to significant seasonal oscillations.

360 Finally, it could be due to regional effects. The model is based on local precipitation.
361 However, the gravity recovery rate variability hypothesis may absorb longer wavelength
362 seasonal effects as well [*van Dam et al.*, 2001; *Crossley et al.*, 2005].

363 A confirmation of the variability of parameter γ (ranging from $0.4 \gamma_0$ to $1.6 \gamma_0$ as results
 364 from Eq. (12) with $A=0.6$) can be obtained by a comparison with the Antecedent
 365 Precipitations Index (API) calculation model [Musy and Higy, 2003; Rosenthal et al.
 366 1982]. The API relates the soil moisture level to the precipitation via the expression:

$$368 \quad API_i = API_{i-1} \cdot K_p + P_{i-1} \quad (15)$$

369
 370 where API_i is the index (mm) at time i , API_{i-1} the index at time $i-1$, P_{i-1} the precipitation
 371 (mm) at time $i-1$ and K_p is a coefficient <1 , that appears strongly correlated to parameter
 372 γ in Eq. (11). Rosenthal et al. [1982] have estimated that in Washita Basin (USA), for a
 373 superficial layer of 15 cm thickness, the value of K_p ranges from 0.84 in July to 0.99 in
 374 December. The correlation between γ and K_p indicates that the local value of γ may range
 375 from $0.1 \gamma_0$ to $1.6 \gamma_0$, where γ_0 represents the yearly average value. Implementing the
 376 tank model with a constant value of γ , the seasonal variations are not absorbed and the
 377 maximum percentage of signal scatter reduction in Walferdange is only 25%.

378

379 **6. Correlation between gravity variation and level of the Alzette River**

380 In this Section, we determine the statistical correlation between the gravity variations
 381 registered by the SG and the water level changes of the Alzette River. The motivation for
 382 this analysis is that hydrological gravity may show a better correlation with river water
 383 levels than precipitation. This is because both gravity and water level changes are
 384 dependent on soil hydrological parameters, whereas rainfall is not.

385 The water level data is available from the Walferdange Meteorological Station 1.63
386 km away and downhill from the WULG (see Figure 2). The direct effect of the water
387 level change on observed gravity variations can be neglected due to the distance between
388 the SG and the river.

389 A shower [Musy and Higy, 2003] is defined as an ensemble of precipitation events
390 related to the same meteorological perturbation. Two showers are considered distinct if,
391 during a defined time interval Δt_s the precipitation height is inferior to a defined level
392 Δh_s [Musy and Higy, 2003]. The water level increase duration Δt_i is defined as the time
393 delay between the start of river level increase and the maximum river level increase due
394 to a particular shower. The mean water level increase duration $\langle \Delta t_i \rangle = 185 \pm 35$ min is
395 calculated for 45 showers sampled between January 2004 and April 2007. In general the
396 same value can be adopted for the parameter Δt_s . The value of Δh_s is the minimum
397 continuous precipitation for which a water level increase can be observed. The values of
398 3 hours and 0.5 mm hour^{-1} are adopted for Δt_s and Δh_m , respectively.

399 In addition to Δt_s and Δh_m , defined as continuity parameters, the quantitative
400 parameters characterizing a shower are the duration (time), the precipitation height (mm),
401 the mean intensity, ratio between the precipitation height and the shower duration, and
402 the maximal intensity [Musy and Higy, 2003].

403 In this section, the time delay between the gravity and water level variations due to the
404 showers and the correlation between the gravity and water level changes are estimated.

405

406 **6.1. Time delay between gravity and water level variations**

407 In order to estimate the time delay of gravity and water level variations, it is more
408 precise to work with the time derivative of the quantities. The sampling interval of the
409 water level time series $L(t)$ is 15 min. The time derivative of $L(t)$ is defined as:

410

$$411 \quad \dot{L}(t) = \frac{L(t + \Delta t) - L(t)}{\Delta t} \quad (16)$$

412

413 The time derivative $\Delta \dot{g}(t)$ of the gravity time series $\Delta g(t)$ is computed in a similar
414 way. Two additional parameters are defined: t_1 is the time delay between the maximum
415 values of the precipitation intensity and the gravity time derivative related to a shower, t_s
416 is the time delay between the maximum values of water level and gravity time derivatives
417 related to a shower (Figure 5).

418 The statistical analysis is made for 30 showers sampled between January 2005 and
419 February 2007. In general, it is difficult to estimate the time delay between the signals as
420 the relationship can be clearly identified only for some type of showers: high intensity
421 showers and medium intensity showers with their maximum intensity concentrated in the
422 initial phase.

423 Figure 5 displays the rainfall height (mm), the gravity time derivative ($\mu\text{Gal hour}^{-1}$)
424 and the water level time derivative (cm hour^{-1}) related to the shower, which occurred on
425 the 25 June 2006.

426

427 **Figure 5**

428

429 The average values and the standard deviation of t_s calculated for the entire sample, for
430 the showers that occurred in the time span April to September (warm months), and for the
431 showers that occurred in the time span October to March (cold months) are presented in
432 Table 1. No substantial differences appear in the values calculated for the three periods,
433 but because of the sample limitation these results must be interpreted with caution.

434

435 **Table 1**

436

437 The average values and the standard deviation of t_l are also calculated for 3 subsets:
438 the entire sample, for the time span April to September (warm months) and the time span
439 October to March (cold months). The results are given in Table 2.

440

441 **Table 2**

442

443 As the uncertainties of the t_l values are even greater than the values themselves, the SG
444 observations do not provide any additional or complementary information already
445 provided by the pluviometer.

446

447

448 **6.2. Correlation between gravity and water level changes as a function of the shower**
449 **height**

450 A statistical analysis of the correlation between the shower heights, the gravity
451 variations and the water level changes is carried out for 45 showers sampled between
452 January 2004 and April 2007.

453 The parameters r_s , Δg_s and L_s are defined as the integrated water content of a shower,
454 the gravity change, and the water level change associated with a shower (Figure 6)
455 respectively. The L_s values as a function of the Δg_s values are displayed in Figure 7.

456

457 **Figure 6**

458

459 The correlation coefficient between L_s and Δg_s is 0.59. The admittance between L_s
460 and Δg_s was calculated to $45 \pm 5 \text{ cm } \mu\text{Gal}^{-1}$

461

462 **Figure 7**

463

464 The L_s values as a function of the r_s values are displayed in Figure 8. The correlation
465 coefficient between L_s and r_s is 0.68, higher than the correlation coefficient between L_s
466 and Δg_s . The admittance of $2.2 \pm 0.4 \text{ cm mm}^{-1}$ between L_s and r_s is calculated. Again, the
467 slightly better correlation between L_s and r_s shows that the SG observations (as compared
468 to predictions based solely on the pluviometer) fail to provide a better insight into river
469 levels.

470

471 **Figure 8**

472

473 **7. Conclusions**

474 A simple tank model, based on a combination of a mass continuity equation and
475 Darcy's law, is implemented in order to evaluate the effects of water storage variations
476 on the gravity observations in Walferdange. The hypothesis of the seasonal variability

477 of the model parameter describing the gravity recovery rate after a rainfall is introduced.
478 No a priori information about soil moisture and groundwater storage is used to estimate
479 the hydrological effects on gravity. The model is based solely on the observed local
480 rainfall and is empirically parameterized.

481 The model reduces the scatter of the SG data by 77%. However, in the absence of the
482 extra seasonal parameter, the maximum percentage of signal reduction is 25%. This
483 result indicates that seasonal effects are important even when looking at short-scale
484 spatial relationships.

485 The time delay between the maximum gravity and water level time derivatives and
486 maximum precipitation intensity and gravity time derivative is 88 ± 34 minutes and 4 ± 9
487 minutes, respectively. The correlation between the gravity and water level variation and
488 the precipitation amount and water level variation is 0.59 and 0.68, respectively. The
489 admittance between water level and gravity variation and water level variation and
490 precipitation amount is 45 ± 5 cm μGal^{-1} and 2.2 ± 0.4 cm mm^{-1} , respectively.

491 In conclusion, the gravity signal does not allow for a better prediction of the water level
492 of the Alzette as compared to the prediction based solely on the pluviometer.

493

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503

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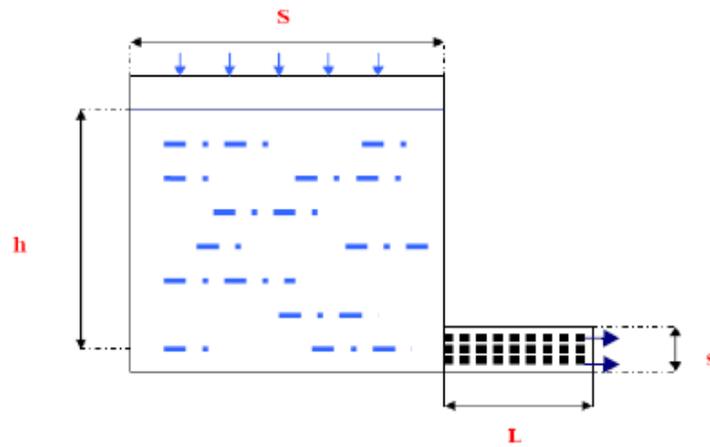
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2 **Fig. 1:** The tank model: S is the tank surface, h the water level, s and L the cross

3 section and length of the plug..

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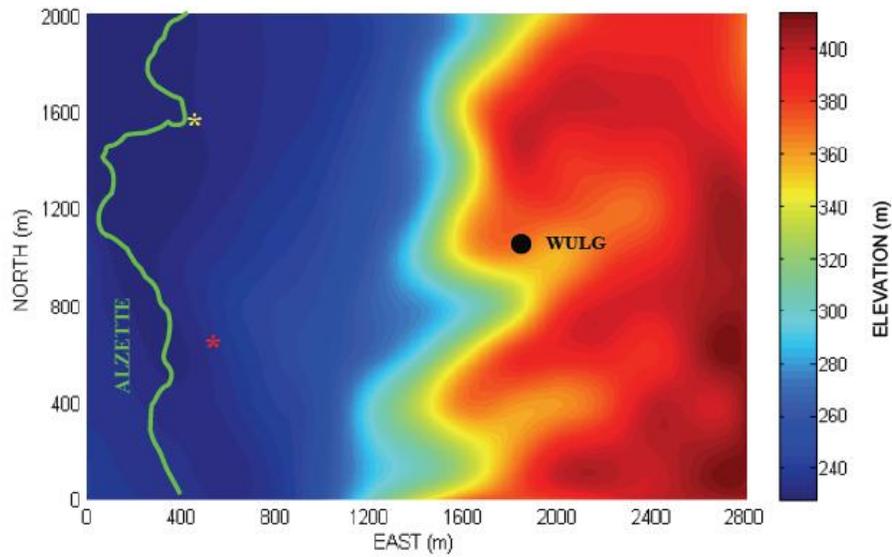
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12 **Fig. 2:** Topography of the area above the WULG (black dot) and Alzette River (green
13 line). The red asterisk represents the WULG pluviometer. The yellow asterisk represents
14 the Walferdange Meteorological Station.

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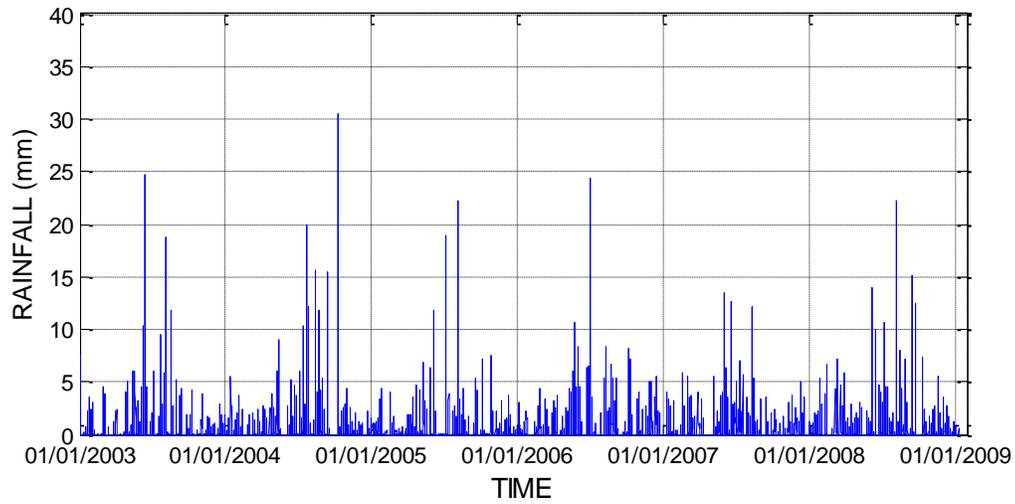
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28 **Fig. 3:** *Input data: Rainfall time series (mm/hour) provided by the WULG for the period*29 *1 January 2003 to 1 January 2009.*

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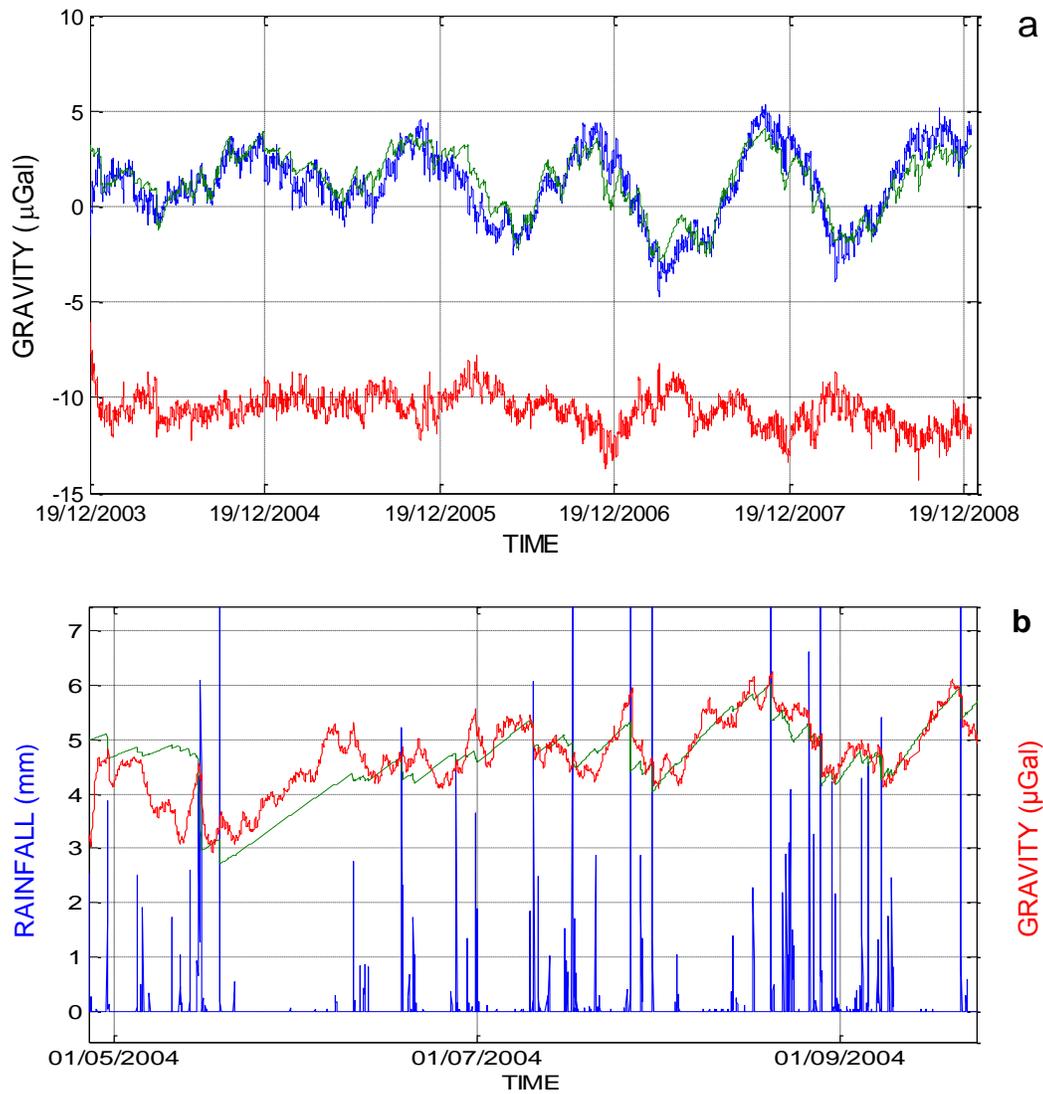
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Fig. 4: Model outputs:

47

a. Observed gravity (blue, μGal), modeled gravity (green, μGal) and their difference (red, μGal) at Walferdange. The comparison period is 19 December 2003 to 1 January 2009.

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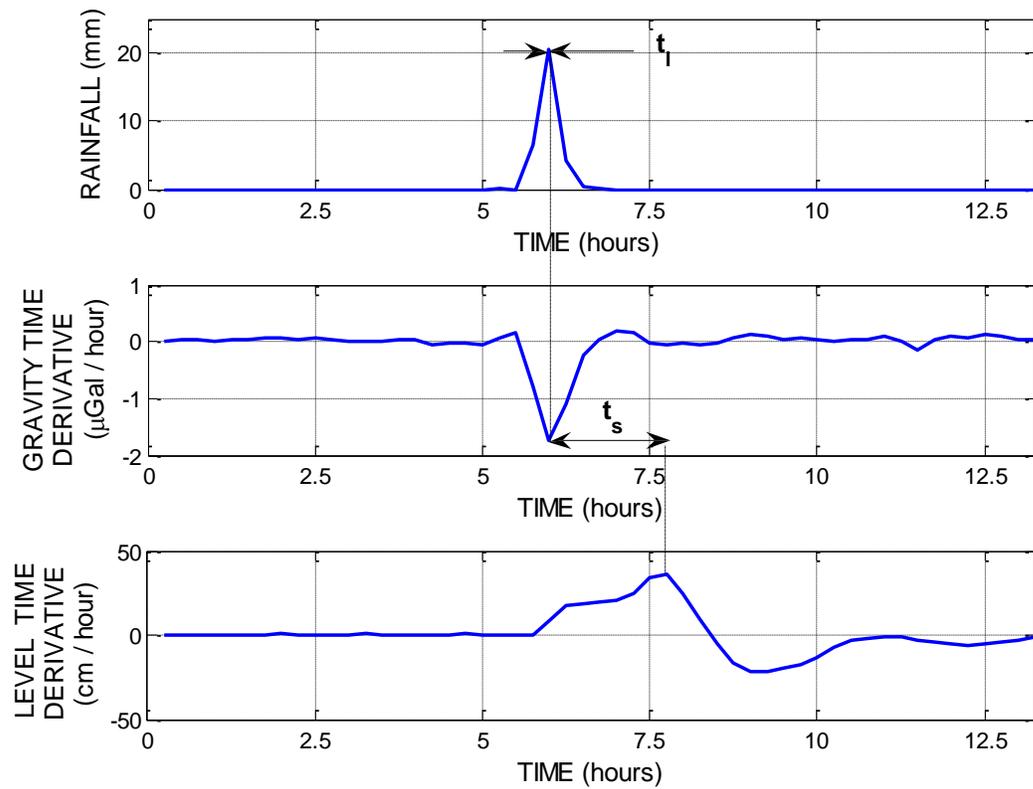
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b. Zoom on a: rainfall (blue, mm/hour), observed gravity (red, μGal), modeled gravity (green, μGal) for the period May to September 2004. The same scale is adopted for gravity and rainfall.

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55 **Fig. 5:** Rainfall height (mm), gravity time derivative ($\mu\text{Gal}/\text{hour}$) and water level time
 56 derivative (cm/hour) related to the shower that occurred on the 25 June 2006.

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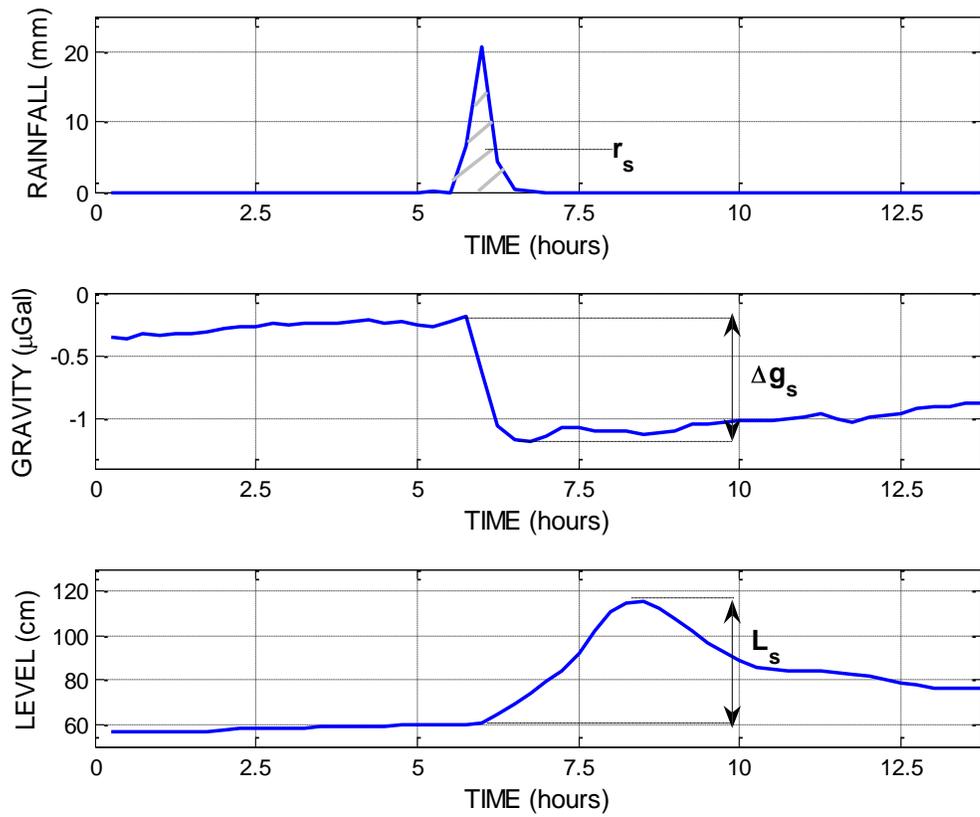
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67 **Fig. 6:** Time evolution of rainfall (mm), gravity (μGal) and water level (cm) related to the

68 shower that occurred on the 25 June 2006.

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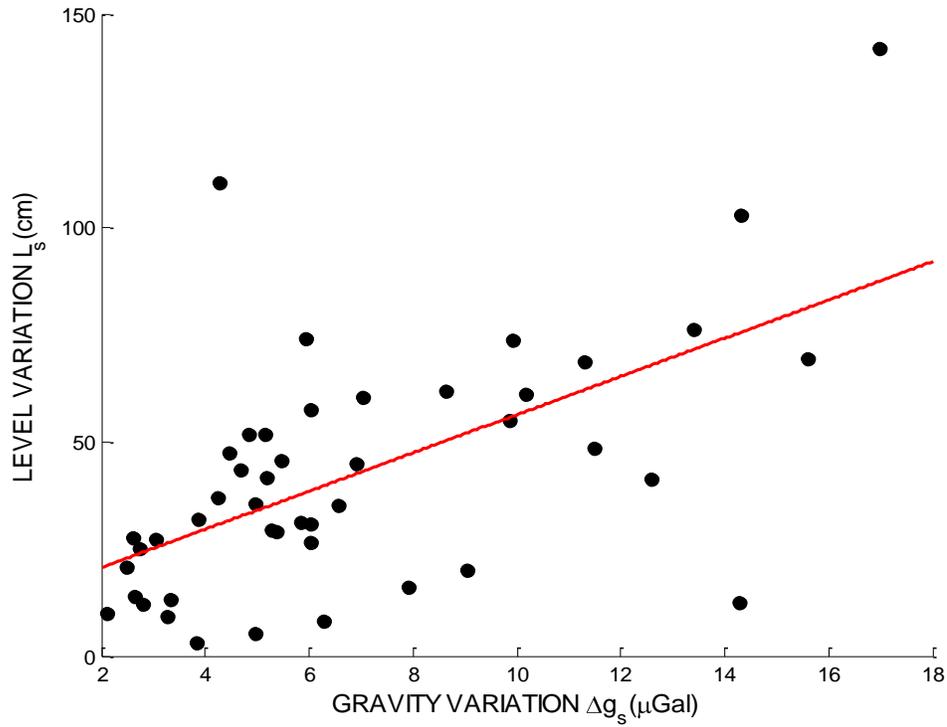
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79 **Fig. 7:** Correlation between gravity and water level changes for the showers between
80 January 2004 and April 2007.

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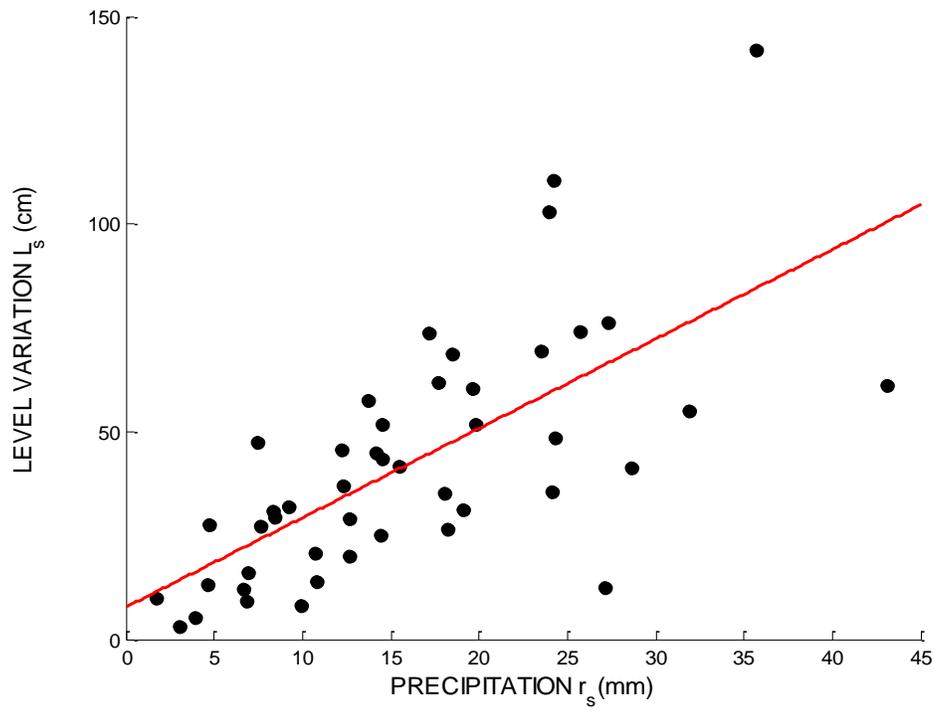
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92 **Fig. 8:** Correlation between precipitation heights and water level changes for the
93 showers between January 2004 and April 2007.

94

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1

	January 2005-February 2007	April-September 2005-2007	October-March 2005-2007
t_s	88 ± 34 min	85 ± 34 min	93 ± 34 min

2

3

4 **Table 1:** Time delay t_s between the maximum values of gravity and water level time
 5 derivatives, for the showers sampled between January 2005 and February 2007.

6

7

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	January 2005-February 2007	April-September 2005-2007	October-March 2005-2007
t_l	4 ± 9 min	5 ± 9 min	1 ± 9 min

11

12

13 **Table 2:** Time delay t_l between the maximum values of shower intensity and gravity time
 14 derivative, for the showers sampled between January 2005 and February 2007.