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8 **Time lag: a methodology for the estimation of vertical and horizontal**
9 **travel & flushing timescales to nitrate threshold concentrations in**
10 **Irish aquifers**

11

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18

19 **Abstract**

20 The Water Framework Directive (WFD) in Europe aims, *inter alia*, to achieve at least
21 “good” water quality status by 2015 by mitigating the causes of pollution. However,
22 with the implementation of programmes of measures in 2012, many catchments may
23 not achieve good water quality status within this timeframe due to the time lag of
24 nutrient transport from source to receptor via hydrological and hydrogeological
25 pathways. An appraisal of catchment time lag issues offers a more realistic
26 scientifically based timescale for expected water quality improvements in response to
27 mitigation measures implemented under the WFD. A simplified methodology for the
28 calculation of nitrate time lag in a variety of Irish hydrogeological scenarios is
29 presented, based on unsaturated vertical and aquifer flushing times required to reach
30 environmental quality standards. Horizontal travel time is estimated for first
31 occurrence of nutrients in a surface water body. The results show that achievement of
32 good water quality status in the Republic of Ireland for some waterbodies may be too

33 optimistic within the current timeframe of 2015 targets but improvements are
34 predicted within subsequent 6 and 12 year cycles.

35

36 **Keywords:** nitrate, time lag; Water Framework Directive; uncertainty analysis

37

38 **1. Introduction**

39 Under the European Union (EU) Water Framework Directive (WFD; 2000/60/EC,
40 OJEC, 2000), River Basin District managers must implement Programmes of
41 Measures (POM) by 2012, within a catchment, where an individual waterbody has
42 been classified as below good status or are at risk of not reaching at least “good
43 ecological status” by 2015. The mitigation of agricultural pollution, notably the
44 transfer of nitrogen (N) and phosphorus (P) from diffuse and point sources, will be
45 part of a suite of mitigation measures to tackle eutrophication in waterbodies
46 throughout the EU.

47 It is widely documented in the literature that many waterbodies in Europe will not
48 achieve the desired water quality status by 2015 due to catchment buffering and long
49 transit times (Cherry et al., 2008). Many River Basin District plans have now reset
50 achievement targets for “good status” to more realistic time reporting periods beyond
51 this timeframe. It is important to note that such time shifts may not be based on
52 hydrological time lags but instead on socio-economic delays. For example, present
53 time lags may be calculated based on practical delays such as: extensive time periods
54 for total implementation of POM in a catchment, or obtaining capital and planning
55 permission to complete a capital projects such as construction of a waste water
56 treatment facility. Also, the choice of POM and their efficacy within a catchment will
57 have an effect on time lag.

58 Hydrological delays may occur where diffuse nutrient transfer predominates in
59 hydrogeological pathways. This delayed hydrological response is also referred to as
60 memory effect, time delay or time lag, and has been highlighted previously (Worrall
61 and Burt, 1999; Bechmann et al., 2008; Iital et al., 2008; Wahlin and Grimvall, 2008)
62 and occurs as nitrate leaching pathways between soils, groundwaters and rivers are
63 generally long and complex (Collins and McGonigle, 2008). Such hydrological time
64 lags also depend on soil/subsoil type, bedrock geology/hydrogeology and climatic
65 factors such as rainfall (Stark and Richards, 2008). The components of hydrological
66 time lag as used in this paper are vertical travel time through the unsaturated zone and
67 flushing of a nitrate contaminated aquifer to below a specified EU water quality
68 target. Time lag through the European aquifer typology (carbonate, unconsolidated,
69 sandstone and hard rock aquifer groups) classification system devised by Wendland et
70 al. (2008) estimated nutrient residence times ranging from days to >1000 year. In
71 many countries, the current estimated time lags of groundwater quality to changes in
72 N inputs are not realistic for baseflow-dominated systems or chalk catchments, where
73 significant retardation of chemicals can occur. Model simulations suggest that
74 groundwater nitrate concentrations in such systems will not decline for several
75 decades after input has been reduced or stopped, and that increases resulting from
76 historical nutrient loading are inevitable within the short term (Jackson et al., 2008;
77 Vertés et al., 2009).

78

79 Hydrological time lags in response to agricultural policy and practice in Europe have
80 differed considerably. For example in several major Eastern European rivers there has
81 been a remarkable lack of response to dramatic decreases in the use of commercial
82 fertilisers since the late 1980's (Grimvall et al., 2000). Large amounts of organic N

83 can accumulate in soil during periods of higher application rates. Therefore nitrogen
84 losses from agricultural runoff will decline very slowly, even though fertiliser inputs
85 have been reduced (Grimvall et al., 2000; Löfgren et al., 1999). State supported
86 agriculture ceased in Finland and Poland in the late 1980's and early 1990's
87 respectively. This led to reduced fertilizer usage but riverine water quality still
88 continued to deteriorate in some areas. In Denmark, intensive application of fertilizers
89 and leaching of nitrate from the soil to groundwater began in the late 1950s. This
90 increased until groundwater nitrate concentrations stabilised in 1980 (Postma et al.,
91 1991). Stringent Danish measures have resulted in a decline in nitrate leaching from
92 the root zone. Determining improvements in Danish ground, coastal and estuarine
93 water is improbable at present, as a result of the time lag factor (Nimmo Smith et al.,
94 2007). A reduction in Denmark's surface water nitrate concentrations has been
95 identified between 1992 and 2002, but this has taken > 20 years (Kronvang et al.,
96 2009).

97

98 In Ireland, 102 groundwater bodies (representing 13.3% of the land area of Ireland)
99 are designated poor status due to elevated groundwater P (Daly, 2009). Where this P
100 is being transported to groundwater from diffuse agricultural sources by diffuse
101 recharge then the recharge principals are similar to nitrate but there will be greater
102 uncertainty as P can be retarded, through adsorption, along its migration pathway due
103 to its non-conservative nature (Corbett et al., 2000). This uncertainty reflects the
104 accumulation of high levels of P in soils and the sorption/desorption processes that
105 occur along the groundwater recharge pathway (Dillon et al., 2003). Schulte et al.
106 (2010) showed that it may take many years for elevated soil P concentrations to be
107 reduced to agronomically and environmentally optimum levels. The extent of these

108 delays were predominantly related to the relative annual P-balance (P balance relative
109 to total P reserves) while the onset of reductions in excessive soil P levels may be
110 observed within five years, this reduction is a slow process and may take years to
111 decades to be completed. In Ireland, only two groundwater bodies (0.3%) have been
112 classified at poor status due to elevated nitrate concentrations in groundwater (Daly,
113 2009). This is based on a mean annual threshold concentration of $37.5 \text{ mg NO}_3^- \text{ L}^{-1}$
114 where there is a sustained upward trend. There is a potential for further groundwater
115 bodies to be classified as “poor” in time if the environmental quality standard (EQS)
116 is lowered. In the future the EQS for groundwater nitrate maybe reduced to combat
117 eutrophication in surface and estuarine waters where N limitation to aquatic plant
118 ecology is identified. The EQS for dissolved inorganic N in estuaries has been set at
119 2.6 mg N L^{-1} (S.I. 272 of 2009). In Ireland, at time of writing there is no EQS in place
120 for rivers.

121

122 The objective of this paper is to estimate the hydrological time lag between
123 implementation of nitrate mitigation measures in 2012 and improvement in
124 groundwater quality using a simplified methodology in a variety of Irish
125 hydrogeological scenarios (Table 1).

126

127 **2. Materials & Methods**

128 This study links a number of modelling approaches to estimate the time lag between
129 implementing measures to reduce nitrate loss to groundwater and the subsequent
130 changes in groundwater and surface water quality. The travel time of the pathway
131 between the soil surface and shallow groundwater (vertical pathway travel time) is
132 estimated based on matrix flow through the vadose zone (Section 2.1). The vertical

133 pathway is the time required for recharge to reach shallow groundwater and either
134 displace or dilute the *in situ* groundwater nitrate concentrations. Where a surface
135 water receptor has elevated nitrate concentrations then the travel time between the
136 groundwater body and the surface water must be accounted for. Horizontal travel time
137 (Section 2.2) estimates the time required for groundwater migration between recharge
138 and discharge, but is not part of the total time lag calculation. Instead it indicates first
139 breakthrough of nutrients from groundwater to surface water. The time required for
140 elevated groundwater nitrate to decrease to acceptable levels (flushing) in response to
141 mitigation measures is estimated based on displacement. The time lag between
142 mitigation measure implementation and groundwater body response is the cumulative
143 travel time in vertical and flushing time lags above. For surface water receptors the
144 time lag is the cumulative time of the hydrological pathways to the river channel.
145 Finally, uncertainty analysis for vertical and flushing time lags is carried out.

146

147 **2.1 Vertical pathway travel time in soil/subsoil**

148 A range of subsoil thicknesses were used: <1m, <3m, 3 - 5 m, 5 - 10 m and >10 m.
149 Such thicknesses were also used by Misstear et al. (2009) when making initial
150 estimates of groundwater recharge from groundwater vulnerability mapping. Vertical
151 travel time is based on matrix flow through these depths of overburden. Where a
152 watertable exists within this overburden, travel times may be shorter (e.g. perched
153 watertable in glacial till) or where the watertable is within the deeper aquifer travel
154 times may be longer e.g. Karst limestone.

155 Based on Fenton et al. (2009) and Lee and Casey (2005) the unsaturated vertical
156 subsurface travel time (Tt in a certain period of ER) can be calculated from equation

157 1.

158
$$Tt = \frac{d}{ER/(\eta_e/100)} \quad [1]$$

159

160 Where ER (m) is mean annual effective rainfall (rainfall-actual evapotranspiration)
161 for a known period and can be estimated for permanent grassland systems in Ireland
162 using the hybrid model developed by Schulte et al. (2005), η_e (%) is average effective
163 porosity (assuming it is a time and space averaged effective porosity) and d is total
164 depth of the unsaturated zone (m) during the same period. A range of η_e values (2.5
165 to 40%) were taken as indicative of various scenarios found in the literature. In
166 general Kilfeather and Van der Meer (2008) found low η_e values for County Laois,
167 Midlands, Ireland but η_e in immature tills were higher giving a range from 1 to 18.9%
168 (pores greater than 25 μm). The mean η_e of 7% is indicative of tills in Ireland,
169 provided immature tills are included. However, a mean of 5% is more appropriate
170 when immature tills are excluded. This could be low if pores $>15 \mu\text{m}$ are considered
171 effective as in Lind and Nyborg, (1998). Till η_e ranges from 2.5 to 32% (pores greater
172 than 15 μm) were found in Sweden (Lind and Nyborg, 1998). Where immature tills
173 were excluded η_e ranged from 3 to 10%. In sandy silty un-weathered Fennoscandian
174 lodgement tills η_e varied from 5 to 10% or less in clayey tills (Haldorsen and Krüger,
175 1990). Such immature till values are low under Irish conditions but are included in the
176 range to be inclusive of all tills. Gibbons et al. (2006) reported subsoil average pore
177 velocities of 6, 7 and 11 mm day^{-1} and the corresponding depths of infiltration would
178 be 2.1, 2.5 and 4.0 m year^{-1} when multiplied over a calendar year. However, recharge
179 and saturated soil porosity does not occur on all days and therefore the pore velocity
180 should be multiplied by the average number of days where soil pores are saturated.

181 Gibbons et al. (2006) concluded that the mean residence time is determined by the
182 recharge (ER and additional irrigation application rates) rate and the water-filled pore
183 space, and not by the K_{sat} that is in the range of 160-1130 mm day⁻¹. This range is at
184 least 40 times greater than the mean rainfall rate of 3-4 mm day⁻¹ during the winter
185 season. Misstear et al. (2008) estimated vertical travel times of recharge through 20 m
186 of low K_{sat} clay till with η_e of 40% to be over 250 years.

187

188 Three typical Irish ER quantities (600, 800 and 1000 mm yr⁻¹) were selected for the
189 estimation of the vertical travel time, based on Schulte et al. (2006). Mean rainfall in
190 Ireland is 1150 mm yr⁻¹. The model estimates ER as a function of soil moisture deficit
191 and evapotranspiration taking antecedent conditions into account. The zero flux plane
192 method is incorporated in this hybrid model, where evaporation occurs above the zero
193 flux plane and below which water moves to the watertable by capillary or gravity
194 effects. On this plane no hydraulic gradient (dh/dx) exists. Drainage rate increases
195 with saturation. The dh/dx also increases proportionally with moisture content.

196

197 These unsaturated zone Tt were compared to saturated zone velocities (v m day⁻¹)
198 calculated using effective Darcian velocity (Equation 2):

199
$$v = -K_{sat} \frac{1}{\eta_e} \frac{dh}{dx} \quad [2]$$

200

201 Where K_{sat} is either within a range of literature values for tills (Misstear et al. 2008;
202 Lind and Lundin 1990) or can be estimated using slug injection or pumping tests
203 (Bouwer and Rice, 1976), dh/dx (50%) is the estimated vertical hydraulic gradient for

204 a point (Mulqueen, 2005). A similar approach was used previously by Helmke et al.
205 (2005) to investigate nitrate transport to groundwater in four Iowa till units.

206

207 Travel time (year) for saturated conditions ($Tt_{(sat)}$) can be calculated from the total
208 unsaturated zone depth (d (m)) using Equation 3.

$$209 \quad Tt_{(sat)} = \frac{d}{v} \quad [3]$$

210

211 **2.2 Horizontal travel time in upper aquifer/shallow groundwater**

212 Horizontal travel times under saturated conditions, although not included in time lag
213 calculation, will indicate the first breakthrough of nutrients at a surface water
214 receptor. Here, piston flow is assumed under steady state conditions. Flows in the
215 saturated zone are a function of the K_{sat} and the potential dh/dx , which in most cases is
216 gravitational. In the saturated zone, K_{sat} remains constant at a particular location but
217 varies spatially, due to the heterogeneity of the aquifer and between different aquifers
218 and geological units. K_{sat} may also vary due to anisotropies in the aquifer. Horizontal
219 travel time estimation (groundwater velocity), was calculated by effective Darcian
220 linear velocity, v (m day⁻¹) as per Eqn. 2. This calculation will estimate the first
221 occurrence of breakthrough at a surface water body and is only indicative of the
222 shortest travel times. Time lag will always be longer than this value.

223 Indicative values of K_{sat} , for gravel ranges from 10² to 10³ m day⁻¹ and when mixed
224 with sand ranges from 5 to 10² m day⁻¹. Addition of clay lenses reduces K_{sat} and the
225 range is from 10⁻³ to 10⁻¹ m day⁻¹. The relationship between K_{sat} , particle size and
226 dh/dx in sand and gravels was investigated thoroughly by Mulqueen (2005), indicating
227 that larger proportions of finer material within a gravel reduces K_{sat} drastically. Fenton
228 et al. (2009) estimated travel times in a sand and gravel aquifer ranged from months to

229 decades due to the presence or absence of clay lenses. Johnson, (1967) gives a list of
230 representative values of specific yield (S_y) for a variety of materials and presents a
231 starting point for gravels 23-25%, limestone – 14% (high for Ireland) and till from 6
232 to 16%. Misstear et al. (2008) estimated S_y parameters based on recharge coefficients
233 –values ranged from 17 to 36% but when extreme values were omitted a more
234 realistic value of 19% was chosen for sand and gravels. Interestingly using a mean S_y
235 of 13% produced unrealistically low recharge coefficient from 40 to 80%. In two
236 synclinal aquifers in the Cork harbour area in southern Ireland, η_e of 1% was found
237 but can be much higher locally (Allen and Milenic, 2001). Similar η_e values are seen
238 in the Waulsortian (2.5%) (Anon, 2005) and Ballysteen limestones (1%) of north
239 Cork, Ireland.

240

241 **2.3 Aquifer Flushing times**

242 Nutrient mixing in the aquifer can be estimated using Equation 4:

$$243 \text{ Nitrate}_{(MIX)} = \frac{\text{Recharge} * \text{Nitrate}_{(R)} + \text{Storage} * \text{Nitrate}_{(I)}}{\text{Recharge} + \text{AquiferT}} \quad [4]$$

244 where Nitrate_(MIX) is the nitrate concentration in the aquifer after mixing, this is the
245 input concentration for the next time step of the mixing model; Recharge is recharge
246 in (m) over an area (m²); Nitrate_(R) is the nitrate concentration (mg L⁻¹) in the
247 recharge, multiplication of these two parameters gives a contaminant flux entering the
248 aquifer; Storage is storage in the aquifer based on the thickness of the aquifer (m),
249 unit width of the aquifer and specific yield (S_y); Nitrate_(I) is the initial nitrate
250 concentration (mg L⁻¹) in the aquifer and AquiferT is aquifer thickness in (m).

251

252 For the examples presented the aquifer is 100 m thick, unit width of 1 m, recharge
253 taken was 0.4 m and S_y of 0.02. The recharge concentrations used were 25, 30 and 35
254 mg $\text{NO}_3^- \text{L}^{-1}$. The model was re-run over incremental time steps (each time step is the
255 equivalent of 0.1 of a year) until the mean annual nitrate threshold value of 37.5 mg
256 $\text{NO}_3^- \text{L}^{-1}$ was reached.

257

258 The minimum time required to reduce groundwater nitrate concentrations below the
259 mean annual threshold of 37.5 mg $\text{NO}_3^- \text{L}^{-1}$ is calculated by cumulating the vertical
260 and flushing times and adding these to the WFD measures implementation year 2012.
261 A range of times was estimated by varying aquifer specific yields of two bedrock
262 aquifers (S_y of 0.01 and 0.02) and a gravel aquifer ($S_y = 0.2$) each with unsaturated
263 zone depths of 3, 5 and 10 m.

264

265 **2.4 Uncertainty analysis**

266 In order to reflect the spatial (and in the case of effective rainfall, temporal) variability
267 of the model input parameters, we applied Monte Carlo analyses to compute the
268 probability density distributions for the unsaturated zone travel time and for the
269 aquifer flushing times.

270 For the Monte Carlo analysis of the unsaturated zone travel time, we assumed a
271 uniform distribution of effective rainfall between 600 mm a^{-1} and 1000 mm a^{-1} , a
272 uniform distribution of thickness of the unsaturated zone between 0 m and 15 m, and
273 a lognormal distribution of the effective porosity, with a mean porosity of 1.800 and a
274 standard deviation of 0.784, based on combined empirical data from Kilfeather et al.

275 (2008) and Lind and Lundin (1990). To quantify the spatio-temporal variability in
276 aquifer flushing times, we developed 8 scenarios Table 1.

277 In addition, to reflect the variability of nitrate concentrations of the recharge entering
278 each of these aquifers, we subjected each of these scenarios to a Monte Carlo analysis
279 with a uniform distribution of initial nitrate concentrations. We assumed a best-case
280 scenario, in which the POM are fully effective and nitrate concentrations in all
281 recharge are below the guideline value of 37.5 mg L^{-1} . Therefore, we assumed that
282 incoming nitrates concentrations were uniformly distributed from a maximum of 37.5
283 mg L^{-1} to a minimum of half this value.

284

285 **3.0 Results**

286 **3.1 Vertical pathway Tt in soil/subsoil**

287 A comparison of methods to estimate vertical flux time is presented in Table 2.
288 Methods 1 (Gibbons et al., 2006), 2 (Gibbons et al., 2006) and 3 (Fenton et al., 2009)
289 all gave similar estimated travel times through varying unsaturated thicknesses
290 ranging from 0.5 years through 0.5 m unsaturated zone thickness to 9.3-10.8 years for
291 10 m unsaturated zone thickness. Method 4 based on Darcian flux under saturated
292 conditions, gave much shorter Tt , compared with methods from 1 to 3, of 0.2 and 4.7
293 years for 0.5 and 10 m unsaturated zone thickness. These times (method 4) reflected
294 the fastest Tt thresholds. As other methods involved some form of unsaturated
295 conditions, Tt were slower. The K_{sat} of tills varies considerably e.g. sandy silty tills in
296 Scandinavia range from $5 \times 10^{-9} \text{ m s}^{-1}$ to $5 \times 10^{-4} \text{ m s}^{-1}$ (Lind and Lundin, 1990). The
297 scenarios covered in this paper represented K_{sat} of moderate permeability tills ranging
298 from $5 \times 10^{-8} \text{ m s}^{-1}$ to $5 \times 10^{-4} \text{ m s}^{-1}$ (Donal Daly, *pers comm.*). Clay tills can have low

299 permeability ($<10^{-9} \text{ m s}^{-1}$) e.g. at a site in Northern Ireland (Phillips et al., 2007) or
300 comparable tills found in Saskatchewan Canada (from 10^{-11} to $10^{-12} \text{ m s}^{-1}$) (Shaw and
301 Hendry, 1998) due to the high η_e .

302

303 The results in Table 2 confirm that the unsaturated travel times are generally 50%
304 longer than the equivalent $Tt_{(sat)}$. The unsaturated zone models all seem to be
305 providing similar estimates of Tt to the saturated zone but these times are highly
306 dependent on the input parameters of ER and η_e . There are negative relationships
307 between ER quantity/ η_e and Tt .

308

309 Vertical Tt in tills of different depths to the saturated zone were estimated for a range
310 of ER quantities and η_e to identify the likely ranges of Tt that can be expected under
311 heterogeneous till properties and meteorological conditions in Ireland (Table 3). Tills
312 may be saturated and unsaturated at different times of the year, so ER only occurs on
313 a set number of days per year. Tt would be expected to vary spatially within
314 catchments due to a combination of till property variation and ER quantities. In areas
315 with lower permeability soils, a proportion of ER would be expected to run laterally
316 over the soil surface or at shallow depths within the soil. The results of this lateral
317 movement would be decreased ER amounts, which would increase the travel time to
318 groundwater in these areas. Conversely areas where lateral flow re-infiltrates in to the
319 soil would have shorter travel times due to increased quantities of drainage water.

320

321 Table 3 presents Tt for recharge to move through tills and sand and gravels. For tills
322 receiving 0.4 m ER, estimated Tt were 1, 0.7 and 0.5 m yr^{-1} for η_e of 40, 30 and 20%.

323 Below such η_e values of 20%, Tt times are faster compared to $Tt_{(sat)}$ conditions as
324 presented in Table 1. There is a positive relationship between ER and Tt . Depths
325 indicative of sand and gravels are 1.5 to 5 m of unsaturated subsoil at 0.4, 0.8 and 1 m
326 ER at η_e of 10, 15, 20 and 30%. The Tt again is influenced by ER. High η_e and low
327 ER result in slower Tt compared to the $Tt_{(sat)}$ equivalent. The $Tt_{(sat)}$ indicates an upper
328 threshold for Eqn.1.

329

330 The response surfaces in Fig. 1 presents estimated vertical Tt (years) for a range of
331 η_e (ranging from 5 to 30%) over a range of annual ER amounts (ranging from 0.4 to 1
332 m yr⁻¹) and a range of depths of the unsaturated zone from 1 to 10 m. The vertical
333 unsaturated zone Tt for η_e 30% (Fig. 1a) illustrates that as subsoil thickness increases
334 to 10 m the Tt increases with decreasing ER. At low ER amounts of 0.4 m yr⁻¹ the
335 vertical Tt can reach approximately 20 years with unsaturated zone thicknesses up to
336 10 m. Less than 50% of the scenarios presented on the surface have Tt in excess of 4
337 years. When η_e is reduced to 20% (Fig. 1b) the Tt scenarios decrease although
338 approximately 25% of the scenarios are still greater than 4 years. As η_e is reduced to
339 10% (Fig.1c) and 5% (Fig. 1d) many of the Tt scenarios are less than 4 years. All of
340 the scenarios are likely to occur at the catchment scale with thinner soils at higher
341 altitudes and subsoil depth increasing as altitude decreases into a valley towards a
342 river. The integration of unsaturated zone depth, η_e and ER can provide catchment
343 managers with more spatially explicit estimates and catchment specific mean time
344 lags of groundwater quality improvements to mitigation measures.

345

346 **3.2 Horizontal travel time**

347 Horizontal travel times indicative of various geological scenarios are presented in
348 Table 3. Tt are determined here in particular by the range of K_{sat} , S_y and dh/dx of 2%.
349 The Tt indicates that migration in sand and gravel aquifers takes longer than all other
350 aquifers to reach sediment at the base (Hyporheic zone) of the surface water receptor.
351 This methodology provides the framework for a range of parameters to be inputted
352 into such tables. An example here would be dh/dx – the figure taken here is 0.2, which
353 of course will vary with K_{sat} . The length of the pathway here was kept the same for all
354 scenarios but within a catchment this will inevitably also be a range of values. Such
355 values are not as important as flushing times to achieve water quality targets but
356 provide upper limits of travel time. Flushing timescales should be longer than first
357 occurrence at a surface water receptor. Such values therefore present a lower range
358 value for time lag.

359

360 **3.3 Time to complete flushing of aquifer**

361 The time it takes for complete flushing to occur should always be longer than the
362 horizontal breakthrough time. However, reducing groundwater nitrate concentrations
363 to below the mean annual threshold value of $37.5 \text{ mg NO}_3^- \text{ L}^{-1}$ may vary depending on
364 the level of mixing and the horizontal pathway taken by the groundwater to the
365 surface waterbody. A certain percentage of the ER will be separated into different
366 pathways and pathway lengths with corresponding travel times. The nitrate
367 concentration leaving the rooting zone and entering the system as recharge will also
368 differ considerably. Assumptions have been made such as a) no natural attenuation or
369 denitrification occurs and b) no vertical mixing. Of course separation into pathways

370 may not be possible in regimes with high K_{sat} e.g. Karst limestone where travel times
371 although fast may range several orders of magnitude.

372

373 In bedrock aquifers with S_y of 0.01 and mean nitrate concentration of $40 \text{ mg NO}_3^- \text{ L}^{-1}$,
374 the estimated time required to decrease to below the threshold value were 0.5, 0.8 and
375 1.8 years, for recharge nitrate concentrations of 25, 30 and $35 \text{ mg NO}_3^- \text{ L}^{-1}$,
376 respectively. Increasing the mean groundwater nitrate concentration to $50 \text{ mg NO}_3^- \text{ L}^{-1}$
377 increased these time lags to 1.8, 2.6 and 4.6 years for recharge nitrate concentrations
378 of 25, 30 and $35 \text{ mg NO}_3^- \text{ L}^{-1}$, respectively. Thus bedrock aquifers with low S_y of 0.01
379 have saturated zone time lags of between 0.5 and 4.6 years depending on the initial
380 groundwater and recharge nitrate concentrations (Fig. 2a). Doubling the S_y of the
381 aquifer doubles the flushing times which then range 1 to 3.6 years and 3.6 to 9.1 years
382 for aquifer with mean initial groundwater nitrate of 40 and $50 \text{ mg NO}_3^- \text{ L}^{-1}$,
383 respectively (Fig. 2b).

384

385 For aquifers with higher S_y the time lags increase considerably. In Ireland, sand and
386 gravel aquifers have the highest S_y typically in the range 0.15 to 0.2. At a typical S_y of
387 0.2 for Irish sand and gravel aquifers, time lags ranged from 1.5 to 5.3 years (Fig. 2a)
388 and from 5.4 to 13.6 years (Fig. 2b) for aquifers with mean initial groundwater nitrate
389 of 40 and $50 \text{ mg NO}_3^- \text{ L}^{-1}$, respectively. The ranges of time lags in sand and gravel
390 aquifers are generally longer than the 1.9 year calculated horizontal travel time for an
391 aquifer with a S_y of 0.14 presented in Table 4.

392

393 The results of the modelling of groundwater flushing indicate that the time required
394 when reducing groundwater nitrate to below the threshold value is strongly influenced

395 by the initial groundwater nitrate concentration. There is a linear increase in time lag
396 with increasing aquifer S_y such that doubling S_y doubles the saturated zone time lag.
397 Further complicating the up-scaling of the model is the relationship between time lag
398 and aquifer recharge quantity. Time lag and recharge quantity are negatively
399 correlated. For example, time lag calculation for: groundwater ($50 \text{ mg NO}_3^- \text{ L}^{-1}$),
400 bedrock aquifer (100 m thick, S_y of 0.02), ER of 200, 400 and 600 mm yr^{-1} (35 mg
401 $\text{NO}_3^- \text{ L}^{-1}$) would be 18.2, 9.2 and 6.2 years, respectively.

402

403 **3.4 Uncertainty Analysis**

404 For the unsaturated zone travel time, the uncertainty analysis (Fig. 3) shows that travel
405 times should amount to two years or less for the vast majority of scenarios. This
406 suggests that longer travel times for the unsaturated zone, evident in Fig. 1 and Table
407 3, while conceivable at local scale, should be rare at national scale, and only occur
408 where in worst case scenarios, with thick soils, high effective porosity and low
409 effective rainfall.

410

411 For the aquifer flushing times, the uncertainty analysis (Fig. 4) shows a wide range of
412 responses. For most scenarios, flushing should be completed within 5-10 years.
413 However, significantly longer flushing times may occur at the local scale, in worst-
414 case scenarios on high-yielding very thick aquifers.

415

416 **4. Discussion**

417 **Vertical Time lag**

418 For all low η_e conditions (Table 3) compared with fully saturated conditions (Table
419 2.) Tt seem faster than expected for <3 m and 3 – 5 m thicknesses but are at or slightly

420 slower than fully $Tt_{(sat)}$ for moderate and low classes. This seems plausible as low η_e
421 mimics unsaturated conditions best. With high ER and high η_e travel times are
422 comparable for saturated conditions for > 10 m thicknesses. In Table 2 Tt for ER of 1
423 m mimics $Tt_{(sat)}$ as η_e is high at 40%, but also because of the dh/dx created by the
424 ER. To have all the Tt values under the threshold set by the fully saturated conditions,
425 more ER is needed (which is doubtful to occur in Ireland) or the η_e is too small in
426 some cases. Such η_e values would allow the inclusion of immature tills. The dh/dx
427 under saturated conditions should also be varied to compare results.

428

429 Sand and gravels from 3 to 5 m thick and with η_e of 10, 20 and 30% are comparable
430 to tills with 5 to 10 m thicknesses.

431

432 Tt calculations seem to work well for the low ER for $\eta_e > 10\%$ where Tt are slower
433 than the $Tt_{(sat)}$ equivalent. Doubling the ER does not allow the correct Tt to be
434 achieved. Bringing the η_e to 20% still achieves slower Tt than $Tt_{(sat)}$ conditions.

435

436 In general, η_e values for gravel and sand are 25% to 40% and 25% to 50%,
437 respectively. When sand and gravel are mixed this η_e decreases, giving a range from
438 20% to 30%. The results from Table 3 agree with this. Stephens et al. (1998) showed
439 that depending on the methodology used to determine η_e in sands and gravels the
440 subsequent results and interpretation may differ considerably. The η_e estimated from
441 geologic logs, measured particle size, and other means were 32%, 31% and 25%

442 respectively. In Ireland, a typical value of η_e for permeable sand and gravels is
443 approximately 20%.

444

445 **Horizontal Travel Time**

446 The horizontal travel time in the Karst aquifer was difficult to estimate as
447 considerable data (S_y , fracture density, fracture truncation, fracture orientation,
448 fracture trace length, fracture spacing, mechanical aperture, effective hydraulic
449 aperture, and aperture opening size) was required to estimate K_{sat} values. A K_{sat} range
450 was available from slug injection tests but was not indicative or comparable with
451 actual horizontal flow travel times. Instead, tracer breakthrough data in several wells
452 originating from the vertical travel time study were used to calculate horizontal travel
453 times. The horizontal travel time to the receptor 500 m away from the source
454 following this pathway was estimated from 2 to 3 months (Fenton et al., 2009).

455

456 **Time to complete flushing of aquifer**

457 The simple model used for estimating aquifer flushing time clearly highlights the
458 importance of nitrate concentration in groundwater, ER and S_y . Increasing the
459 groundwater initial nitrate concentration from 40 to 50 mg $\text{NO}_3^- \text{L}^{-1}$, increased the
460 time lag by between 2.5 and 3.6 fold depending on ER nitrate concentration.
461 Temporal variation in both recharge and groundwater nitrate concentration makes
462 refining the model further problematic. The model proposed does not account for
463 denitrification along the nitrate transport pathway. Denitrification in the saturated and
464 unsaturated zones can further reduce ER and groundwater nitrate concentrations. This
465 can reduce the time required to achieve the mean annual threshold value of 37.5 mg
466 $\text{NO}_3^- \text{L}^{-1}$. Groundwater denitrification has been shown to be an important attenuation

467 process and is controlled by substrate availability (N and C), oxygen/redox status and
468 denitrifier occurrence. These conditions vary both temporally and spatially and
469 denitrification has been shown to be important in controlling groundwater nitrate
470 occurrence (Fenton et al. 2009).

471

472 **Cumulative time lag**

473 Integrating the estimated unsaturated zone travel times and the time lag in reducing
474 groundwater nitrate concentrations as estimated by the groundwater mixing model
475 gives an idea of the total time lag that can be expected. Integrated cumulative travel
476 times have been calculated (Fig. 5). Unsaturated zones Tt were based on η_e 0.3 and
477 unsaturated zone depths of 3, 5 and 10 m. Aquifer time lag was calculated for bedrock
478 aquifers with S_y of 0.01 and 0.02 and gravel aquifers with S_y of 0.2, the criteria for the
479 mixing model were that initial groundwater nitrate was $50 \text{ mg NO}_3^- \text{ L}^{-1}$ and ER nitrate
480 concentration of $35 \text{ mg NO}_3^- \text{ L}^{-1}$. The estimated cumulative time lags are based on the
481 current state of knowledge and data availability. Increasing the temporal and spatial
482 understanding of hydrogeological characteristics will improve the accuracy of the
483 time lag estimation.

484 Based on the scenario outlined above cumulative time lag for areas with unsaturated
485 zone depths of 3 m were 6.9, 11.3 and 15.9 years for bedrock aquifers with S_y of 0.01
486 and 0.02 and gravel aquifers. Thus groundwater bodies with these characteristics with
487 measures introduced in 2012 the minimum likely year to achieve good status between
488 2019 and 2028. For measures introduced in 2009 then minimum likely year to achieve
489 good status between 2016 and 2025. Increasing unsaturated zone depth to 5 m
490 increases the time lag slightly to between 8.4 and 17.4 years from the introduction of
491 measures and this only slightly increases cumulative time as it only influences the Tt

492 in this zone. Further increasing the unsaturated zone depth to 10 m increases the
493 cumulative time lag to between 12.1 and 21.1 years. In areas with thicker unsaturated
494 zone thicknesses of 10 m the minimum likely year to achieve good status for
495 measures introduced in 2012 would be between 2024 and 2033 (Fig. 6).

496 The minimum year for groundwater nitrate to reduce from 50 to below 37.5 mg L⁻¹,
497 based on the unsaturated and saturated zone time lags, are presented for each aquifer
498 by S_y combination. Karstified or fracture rock aquifers, with low S_y of 0.01, the
499 minimum year to reduce nitrate concentrations are between 2019 and 2024 depending
500 on the unsaturated zone thickness. In the same bedrock aquifers, with higher S_y of
501 0.02, this minimum time increases to between 2023 and 2029, depending on the
502 unsaturated zone depth.

503 Failure of the WFD to recognise climate change remains a major short coming of such
504 a legislative instrument. Climate change will have implications for mitigation option
505 efficacy and groundwater response time lags. Expected changes in hydrology as a
506 consequence of climate change may involve rainfall, evapotranspiration, runoff and
507 effective rainfall alterations specific to a geographical location. In carbonate aquifers
508 across Europe, research under the Groundwater Resources and Climate Change
509 Effects (GRACE) program shows that factors such as recharge increase and lowering
510 of the watertable are possibilities due to climate change. This coupled with heightened
511 CO₂ levels in the atmosphere could cause increased dissolution of carbonate aquifers
512 thereby changing their permeability and storage. In other areas, increased rainfall
513 intensity could reduce recharge as more rainfall moves by overland flow rather than
514 infiltrating into the soil. Such matters would re-define hydrological time lags over
515 time but would still be within the ranges estimated in this paper.

516 Application of spatially explicit estimates of model input parameters will help
517 catchment managers identify catchment specific time lags. Realistic timescales for
518 groundwater quality improvements should be communicated with land managers so
519 that they can appreciate the time required for their land management practices to
520 impact on groundwater quality.

521 The time lag between introducing protection measures to reduce N inputs in 2012 and
522 first improvements in water quality in 2015 is therefore likely to occur at different
523 rates in different catchments comprising different soils and geologies and should be
524 considered by policy makers and catchment managers (Kronvang et al., 2008).

525 **Uncertainty Analysis**

526 The outcomes of the uncertainty analyses depend to a significant degree on the
527 assumed distribution of the model variables, and the associated parameters of these
528 distributions. In other words, if different distribution parameters had been assumed,
529 different outcomes may have been expected.

530

531 The lognormal distribution and associated parameters were calibrated and employed
532 to one of the most important variables, i.e. effective porosity, against empirical data
533 by Kilfeather et al. (2008) and Lind and Lundin (1990). For the distributions of the
534 remaining data, we based our range (maxima and minima) on empirical data. In
535 absence of detailed information on the probability density distributions of these
536 variables, we employed the uniform distribution as the most parsimonious
537 distribution.

538 In summary, the frequency distributions of both the unsaturated and aquifer flushing
539 times should be interpreted as indicative distributions only that demonstrate the range
540 of travel and flushing times that may reasonably be expected. Further empirical
541 studies have now been initiated and are ongoing to collect empirical distribution data
542 on some of the remaining model input variables.

543 **Total Nitrogen**

544 At present the EQS for European freshwaters and salt waters are set. Moves towards
545 setting EQS for total nitrogen (TN) are being considered across much of Europe as
546 nitrate only accounts for 50-60% of the TN flux especially in lowland permeable
547 groundwater fed catchments. TN is composed of total kjeldahl nitrogen (organic and
548 reduced nitrogen), ammonia, nitrates and nitrites. Proposed limits or EQS emerging
549 from work reviewed by the European Nitrogen Assessment (ENA) are 2 mg TN L⁻¹
550 for Lakes and 1.3 mg L⁻¹ to 2 mg L⁻¹ for salt waters (Johnes, 2010). This reflects a key
551 change point in freshwater systems where reactive nitrogen becomes the dominant
552 fraction of the TN load. Moving forward, this has challenging consequences for
553 estimation of time lag. With such EQS, denitrification, nitrification and mineralisation
554 would need to be accounted for in time lag estimation.

555

556 **Benefits for policy makers**

557 A lack of relevant and timely “lag” estimation, hamper the effective dissemination of
558 results to relevant stakeholders. From uncertainty analysis the efficacy of mitigation
559 measures will not manifest themselves for up to 10 years. Incorporation of time lag
560 principles into future water quality regulations will provide regulators with realistic
561 expectations when implementing policies. In Ireland, the Nitrates Directive is the
562 main POM in place to meet the goals of the WFD. The Agricultural Catchments

563 Programme aims to pick up on early changes in water quality and in doing so can give
564 guidance with regard to the efficacy of measures (Fealy et al., 2010).

565

566 **5. Conclusions**

567 The issue of hydrogeological time lag is not addressed within the WFD between
568 implementation of catchment mitigation measures and expectations towards target
569 dates. This period of time is related to the implementation of management rather than
570 an appraisal of catchment hydrogeological processes and characteristics. Realistic
571 timescales for achievement of good status for groundwaters or groundwater
572 dominated surface waters must be based on estimates of catchment specific time lags.
573 The simplified methodology in this paper provides reasonable estimates of time lags
574 that could be anticipated in common Irish hydrogeological settings. Based on the
575 simplified unsaturated zone travel time and aquifer mixing models achieving the
576 WFD of good status for all waters by 2015 is unrealistic for groundwater bodies with
577 reasonably long transport pathways but with reasonable expectations within future
578 reporting cycles. This work highlights, that the minimum year for measures
579 introduced in 2012 to reduce groundwater nitrate concentrations to mean annual
580 threshold values, ranges from 2019 to 2033 depending on the specific unsaturated
581 zone depth and aquifer thickness and S_y . Therefore, time lags offer justification in
582 some scenarios to extend target dates for achieving good water quality status based on
583 present POM. Furthermore, incorporation of these principles into regulations that may
584 require more challenging N standards in the future (other than drinking water
585 standards), and especially in groundwater fed surface waters such as some river and
586 estuarine systems, will provide regulators with realistic expectations when managing
587 towards target dates.

588

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595 **Captions for Tables**

596 Table 1 Scenarios used for unsaturated and flushing travel time

597

598 Table 2 Summary of four methods used to estimate the vertical travel time through

599 variable unsaturated zone thicknesses of 0.5 to 10 m with an η_e of 0.37 under

600 saturated conditions (hydraulic gradient =1) representing the fastest vertical travel

601 times. Travel times under unsaturated conditions will be longer than these best case

602 scenarios.

603

604 Table 3 Travel time for recharge to move through varying till of unsaturated subsoil at

605 0.4, 0.8 and 1 m ER at η_e of 2.5, 5, 10, 20 30 and 40%.

606

607 Table 4 Horizontal travel time to a receptor 500 m away- this reflects first arrival.

608 Flushing times should always be longer than this time (for 2% dh/dx)

609 **Captions for Figures**

610 Fig 1 - Unsaturated zone travel time (yrs) through varying unsaturated zone depths at
611 a range of ER amounts (m yr^{-1}) for (a) η_e of 30%, (b) η_e of 20%, (C) η_e of 10% and
612 (d) η_e of 5%.

613

614 Fig 2 - Time lag to reduce groundwater nitrate concentrations in areas with annual
615 recharge rates of 400 mm yr^{-1} for aquifers with mean initial nitrate concentrations of
616 A: $40 \text{ mg NO}_3^- \text{ L}^{-1}$ and B: $50 \text{ mg NO}_3^- \text{ L}^{-1}$, to below the EPA groundwater mean
617 annual nitrate threshold of $37.5 \text{ mg NO}_3^- \text{ L}^{-1}$ for bedrock aquifers (rock) 100 m thick
618 with S_y of 0.01 and 0.02 and gravel aquifers (gravel) 15 m thick with S_y of 0.15 and 0.2
619 at ER nitrate concentrations of 25, 30 and $35 \text{ mg NO}_3^- \text{ L}^{-1}$.

620

621 Fig 3 - Frequency distribution of vertical travel times due to different ER, η_e and
622 unsaturated zone thicknesses

623

624 Fig 4 - Frequency distribution of time lags due to flushing in bedrock and sand and
625 gravel aquifers based on the scenario outlined in Table 1.

626

627 Fig 5 - Cumulative time lag for reducing groundwater nitrate to below the mean
628 annual threshold of $37.5 \text{ mg NO}_3^- \text{ L}^{-1}$ for bedrock aquifers with S_y of 0.01 and 0.02
629 and for gravel aquifers ($S_y = 0.2$) with 400 mm ER , groundwater nitrate of 50 mg NO_3^-
630 L^{-1} and ER nitrate of $35 \text{ mg NO}_3^- \text{ L}^{-1}$ at a range of unsaturated zone depths of 3, 5 and
631 10 m.

632

633 Fig 6 - Minimum year for reducing groundwater nitrate concentrations to below the
634 mean annual threshold of $37.5 \text{ mg NO}_3^- \text{ L}^{-1}$ for two bedrock aquifers (S_y of 0.01 and
635 0.02) and a gravel aquifer (S_y - 0.2) with measures introduced in 2012. For each
636 aquifer type the three points relate to unsaturated zone depths of 3, 5 and 10 m.

637

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Table 1. Scenarios used for unsaturated and flushing travel time

Unsaturated zone				
Scenario	Soil depth (d)	Effective porosity (η_e)	Effective Rainfall (ER)	
	m	%	m	
1-30	0.5, 2, 3, 5, 10	2.5, 5, 10, 20, 40	0.4, 0.8, 1.0	
Aquifer flushing				
Scenario	Aquifer	Sy	Aquifer thickness	Nitrate (mg L^{-1})
		(%)	(m)	
1	Bedrock	1	100	40
2	Bedrock	2	100	40
3	Bedrock	1	100	50
4	Bedrock	2	100	50
5	Sand and Gravel	20	15	40
6	Sand and Gravel	20	15	50
7	Sand and Gravel	20	100	40
8	Sand and Gravel	20	100	50

Table 2 Summary of four methods used to estimate the vertical travel time through variable unsaturated zone thicknesses of 0.5 to 10 m with an η_e of 37% under saturated conditions (hydraulic gradient =1) representing the fastest vertical travel times. Tt under unsaturated conditions will be longer than these best case scenarios.

	Gibbons et al (2006) Method 1	Gibbons et al (2006) Method 2	Fenton et al (2009) Method 3	Missstear et al (2009) Method 4
	Travel time (Tt) (yr)			
Depth (m)				
0.5	0.5	0.5	0.5	0.2
2	1.9	2.2	1.9	0.9
3	2.8	3.2	2.8	1.4
5	4.7	5.4	4.6	2.4
10	9.4	10.8	9.3	4.7
Method 1	Gibbons et al. (2006) Pore velocity =2.9mm yr ⁻¹ which is calculated based on pore velocity/number of days drainage			
Method 2	Gibbons et al. (2006) $T(t) = ER (400 \text{ mm}) / \text{depth (m)} * \eta_e (37\%)$			
Method 3	Fenton et al. (2009) $\text{Depth} / ((ER / \eta_e) * \text{time})$			
Method 4	Missstear et al. (2009) Darcian flux method with $k=5*10^{-8}$, η_e of 37% and hydraulic gradient of 1			

Table 3 Travel time for recharge to move through varying till of unsaturated subsoil at 0.4, 0.8 and 1 m ER at η_e of 2.5, 5, 10, 20 30 and 40%.

Depth (m)*	η_e %	Travel time (yr) for variable Effective rainfall (m)		
		0.4	0.8	1.0
0.5	40	0.5	0.3	0.2
2	40	2.0	1.0	0.8
3	40	3.0	1.5	1.2
5	40	5.0	2.5	2.0
10	40	10.0	5.0	4.0
0.5	30	0.4	0.2	0.2
2	30	1.5	0.8	0.6
3	30	2.3	1.1	0.9
5	30	3.8	1.9	1.5
10	30	7.5	3.8	3.0
0.5	20	0.3	0.1	0.1
2	20	1.0	0.5	0.4
3	20	1.5	0.8	0.6
5	20	2.5	1.3	1.0
10	20	5.0	2.5	2.0
0.5	10	0.1	0.1	0.1
2	10	0.5	0.3	0.2
3	10	0.8	0.4	0.3
5	10	1.3	0.6	0.5
10	10	2.5	1.3	1.0
0.5	5	0.1	0.0	0.0
2	5	0.3	0.1	0.1
3	5	0.4	0.2	0.2
5	5	0.6	0.3	0.3
10	5	1.3	0.6	0.5
0.5	2.5	0.0	0.0	0.0
2	2.5	0.1	0.1	0.1
3	2.5	0.2	0.1	0.1
5	2.5	0.3	0.2	0.1
10	2.5	0.6	0.3	0.3

Table 4. Horizontal travel time to a receptor 500 m away- this reflects first arrival. Flushing times should always be longer than this time (for 2%

dh/dx)

Aquifer Class	Class		S_y	K_{sat} m day ⁻¹	dh/dx^* %	v m day ⁻¹	v_e m day ⁻¹	to 500 m yr
Rk	Regionally important	Pure limestone	0.01	5	2	0.1	10.0	0.14
Rf	Regionally important		0.02	5	2	0.1	5.0	0.27
Rg	Regionally important	Sand & gravel	0.2	5	2	0.1	0.5	2.74
Lm	Locally important		0.010	2	2	0.04	2.4	0.57
Lg	Locally important	Sand & gravel	0.200	2	2	0.04	0.2	6.85
Ll	Locally important		0.016	1	2	0.02	1.2	1.13
Pl	Poorly productive	Impure limestone	0.009	1	2	0.02	2.2	0.62
Pu	Poorly productive	Unweathered granite	0.0009	1	2	0.02	22.2	0.06

* dh/dx will change depending on K_{sat} .

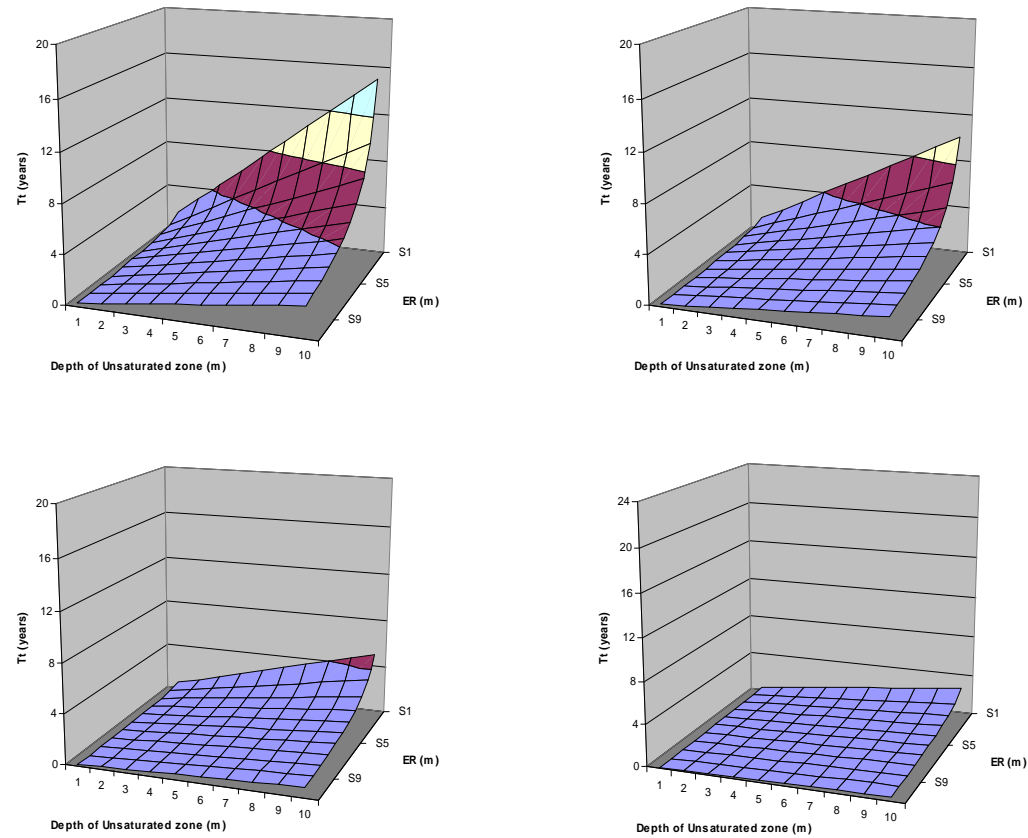


Fig 1 - Unsaturated zone Tt (yr) through varying unsaturated zone depths at a range of ER amounts (m in a particular time period) for (a) η_e of 30%, (b) η_e of 20%, (c) η_e of 10% and (d) η_e of 5%.

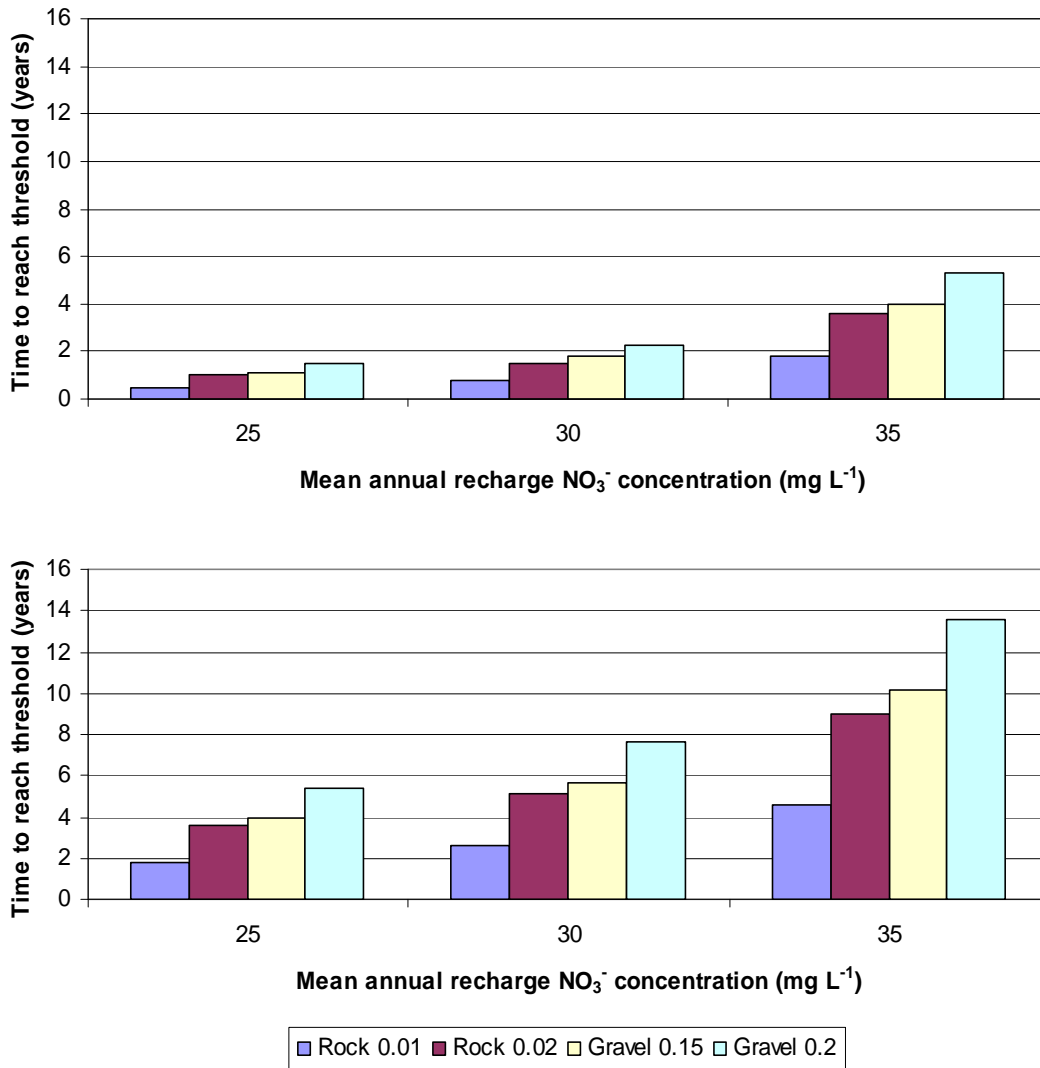


Fig 2 - Time lag to reduce groundwater nitrate concentrations in areas with annual recharge rates of 400 mm yr⁻¹ for aquifers with mean initial nitrate concentrations of (a) 40 mg NO₃⁻ L⁻¹ and B: 50 mg NO₃⁻ L⁻¹, to below the EPA groundwater mean annual nitrate threshold of 37.5 mg NO₃⁻ L⁻¹ for bedrock aquifers (rock) 100 m thick with *S_y* of 0.01 and 0.02 and gravel aquifers (gravel) 15 m thick with *S_y* of 0.15 and 0.2 at ER nitrate concentrations of 25, 30 and 35 mg NO₃⁻ L⁻¹.

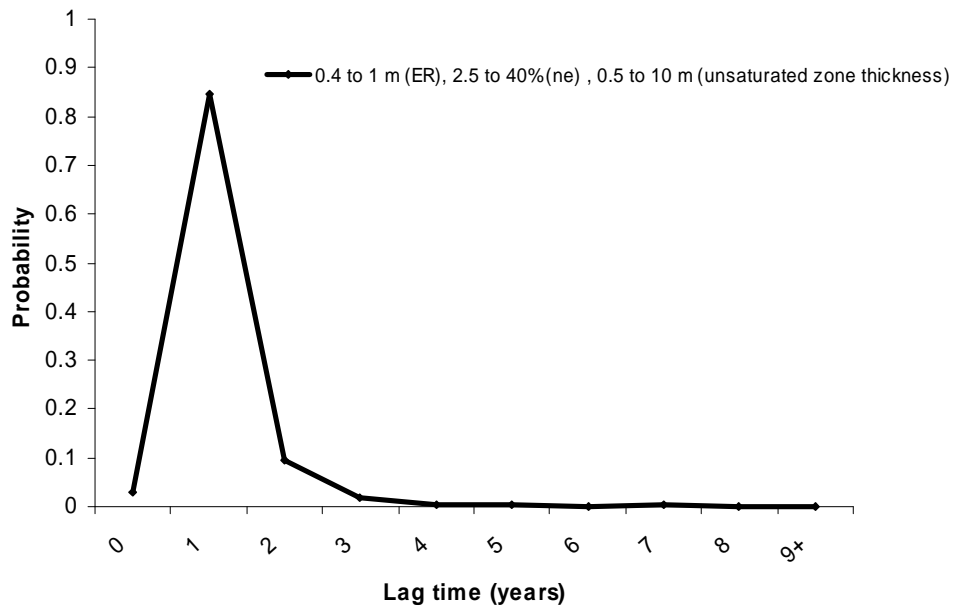


Fig 3 - Frequency distribution of vertical travel times due to different ER, η_e and unsaturated zone thicknesses

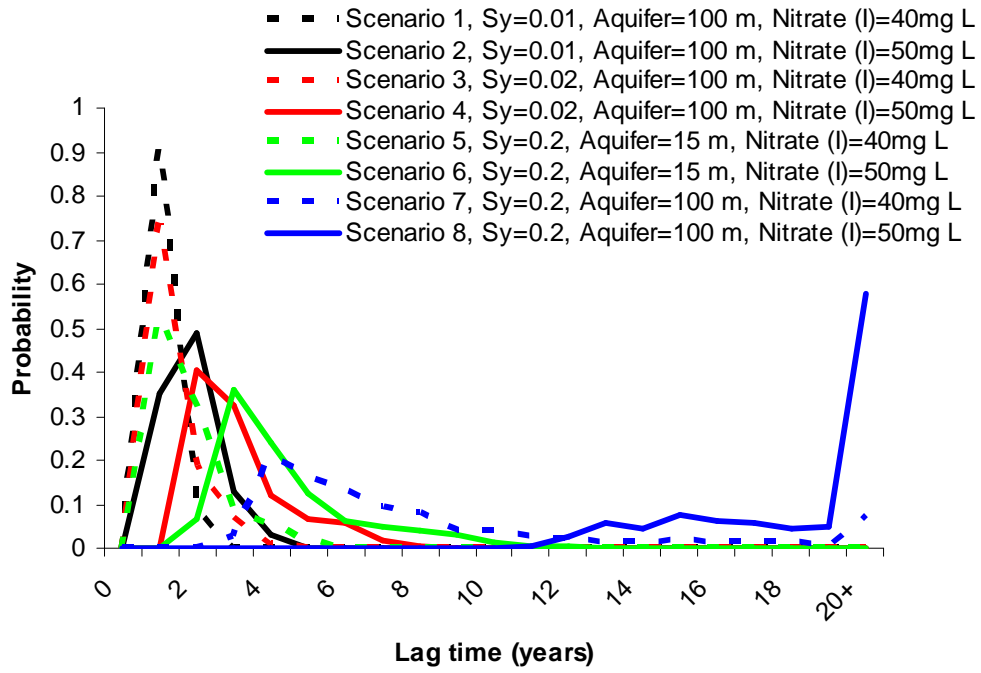


Fig 4 - Frequency distribution of time lags due to flushing in bedrock and sand and gravel aquifers based on the scenario outlined in Table 1.

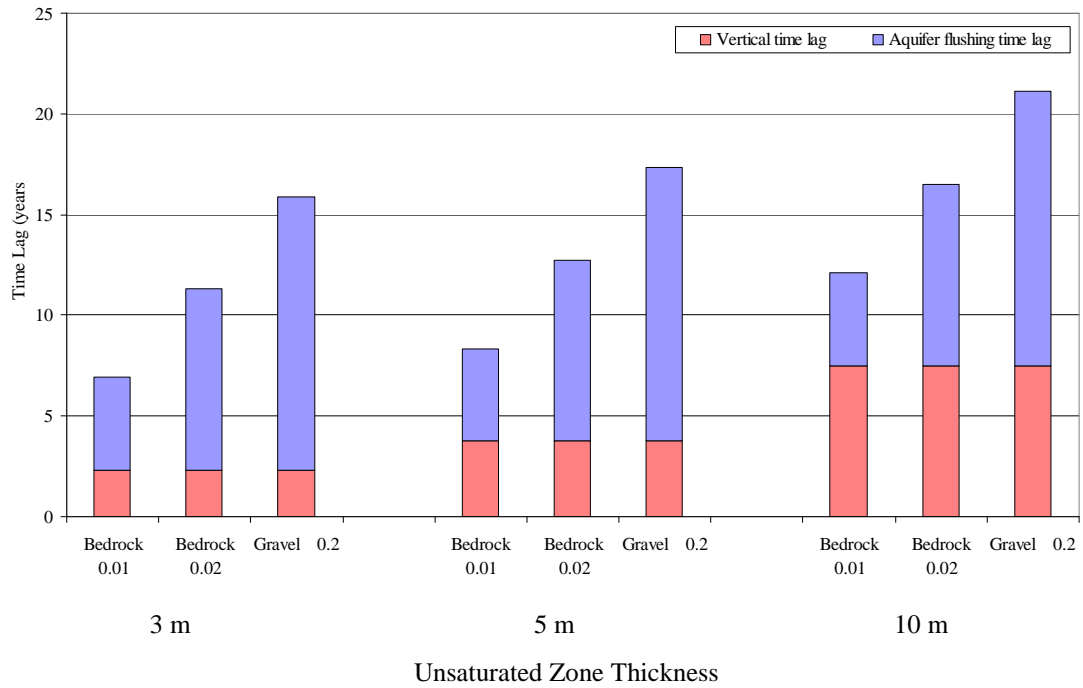


Fig 5 - Cumulative time lag for reducing groundwater nitrate to below the mean annual threshold of $37.5 \text{ mg NO}_3^- \text{ L}^{-1}$ for bedrock aquifers with S_y of 0.01 and 0.02 and for gravel aquifers ($S_y = 0.2$) with 400 mm ER, groundwater nitrate of $50 \text{ mg NO}_3^- \text{ L}^{-1}$ and ER nitrate of $35 \text{ mg NO}_3^- \text{ L}^{-1}$ at a range of unsaturated zone depths of 3, 5 and 10 m.

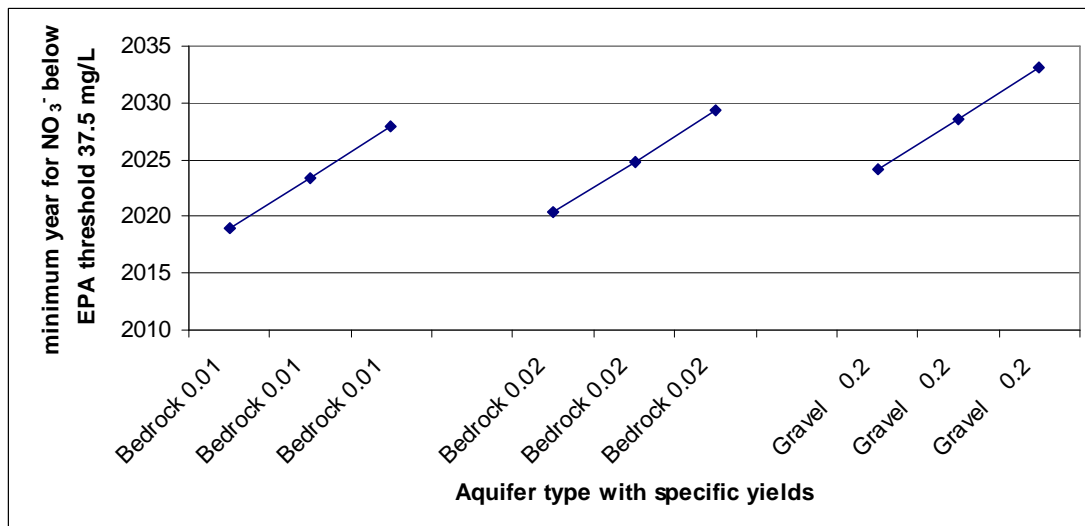


Fig 6 - Minimum year for reducing groundwater nitrate concentrations to below the mean annual threshold of $37.5 \text{ mg NO}_3^- \text{ L}^{-1}$ for two bedrock aquifers (S_y of 0.01 and 0.02) and a gravel aquifer ($S_y = 0.2$) with measures introduced in 2012. For each aquifer type the three points relate to unsaturated zone depths of 3, 5 and 10 m, respectively.