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1 **Simple deterministic model of the hydraulic buffer effect in septic** 2 **tanks**

3 Nicolas Forquet¹ and Matthieu Dufresne²

4 **Abstract**

5 Septic tanks are widely used in on-site wastewater treatment systems. In addition to anaerobic pre-
6 treatment, hydraulic buffering is one of the roles attributed to septic tanks. However there is still no
7 tool for assessing it, especially in dynamic conditions. For gravity fed-system, it could help both
8 researchers and system designers. This technical note reports a simple mechanistic model based on the
9 assumption of flow transition between the septic tank and the outflow pipe. The only parameter of this
10 model was calibrated using CFD modeling for a wide range of discharge rates. The resulting model
11 highlights that a septic tank plays a hydraulic buffer role when faced with sudden and large discharge
12 flow but this role tends to disappear when input hydrographs are smoother. In those cases there is an
13 observable lag between the input hydrograph and outflow hydrograph.

14 **Key words:** on-site wastewater treatment – septic tank – buffer effect – mechanistic modeling

15 **Introduction**

16 On-site wastewater systems usually consist of a septic tank followed by a treatment unit. In many
17 countries (including the USA and France), treatment units are commonly gravity-fed from the outlet of
18 the septic tank (e.g. a drainfield trench or vertical flow sand filter). Because flow at the outlet of a
19 septic tank is not constant, the distribution over the surface of the treatment unit is rather uneven,
20 especially in early filter operation (Bridson-Pateman et al., 2013; Gill et al., 2009). Flow variability
21 stems mainly from household water usage patterns, but the septic tank also induces some flow
22 modulation. The hydraulic buffer effect of septic tanks is often cited but to our knowledge there is still
23 no method for quantifying it. It is often assumed that for the purposes of studying of long-term
24 phenomena (like clogging of the treatment unit at month-long or year-long scale), the outflow can be
25 considered constant (Winstanley & Fowler, 2013). However, as we gain progressively more
26 knowledge on the actual hydrograph produced by a household, it may be interesting to quantify how
27 effectively the septic tank can buffer large inflow rates. This may be of particular interest for
28 estimating the efficiency of gravity-driven distribution on secondary treatment unit and to eventually
29 optimize it.

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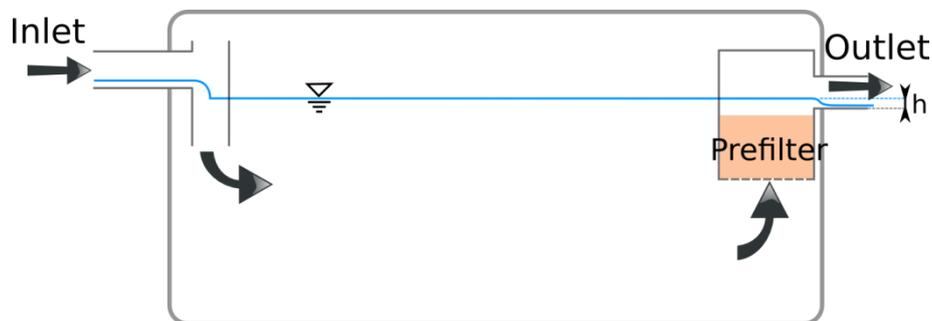
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30 Two possible approaches were identified: (i) using a tank model where the law governing outflow is
 31 obtained by a statistical learning or neural network method (Vazquez et al., 1999) or (ii) the overflow
 32 analogy. A statistical learning or neural network method is able to mimic complex hydraulic systems
 33 without the need to compile advanced knowledge of the constitutive elements. However, it requires a
 34 large dataset for model learning, which is not compatible with our needs. The overflow analogy is
 35 based on a simple mechanistic approach based on the assumption that critical flow occurs at the outlet
 36 of the septic tank. In this paper, we briefly present the model and its practical implementation, and
 37 then report selected results based on several hydrographs.

38 Model presentation

39 Model equations

40 Figure 1 presents a sketch of the usual design of a septic tank. The upstream section of the outflow
 41 pipe of a septic tank is a local maximum of the bottom profile. With no downstream influence
 42 (guaranteed by the large slope of the pipe, which is usually over 0.5%; AFNOR, 2007), this
 43 configuration is responsible for producing critical flow (Hager 1999). Critical flow is the transition
 44 between subcritical flow (here, a nearly horizontal water surface with a very small velocity in the
 45 septic tank) and supercritical flow (here, a fast flow in the outflow pipe). The occurrence of critical
 46 flow guarantees a direct relationship between water level h in the tank and the outflow discharge (Q_{out}
 47 [L^3T^{-1}]). We used this relationship in association with a water mass balance in the septic tank to build
 48 a time-dependent model.

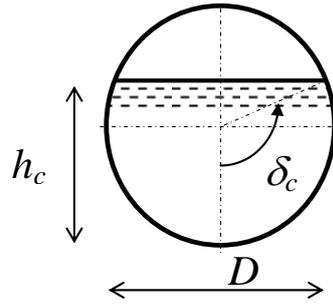


49
 50 **Figure 1. Sketch of the water flow through a septic tank**

51 The discharge Q_{out} corresponding to the critical water depth h_c [L] can be evaluated considering a
 52 Froude number equal to unity (transition from subcritical to supercritical flow), according to:

$$53 \quad Q_{out} = S_c \sqrt{g D_{hc}} \quad (1)$$

54 where Q_{out} is outflow discharge [$L^3 T^{-1}$], S_c is critical cross-section [L^2], g is gravitational acceleration
 55 [$L T^{-2}$] and D_{hc} is critical hydraulic diameter [L]. Both S_c and D_{hc} are linked to the critical water depth
 56 (h_c) by relationships (Equations 2, 3 and 4) using the angle δ_c as illustrated in Figure 2.



57

58

Figure 2. Relationships between critical water depth and hydraulic section and pipe diameter

59
$$S_c = \frac{D^2}{4} (\delta_c - \sin \delta_c \cos \delta_c) \quad (2)$$

60
$$D_{hc} = \frac{D(\delta_c - \sin \delta_c \cos \delta_c)}{4 \sin \delta_c} \quad (3)$$

61
$$h_c = \frac{D}{2} (1 - \cos \delta_c) \quad (4)$$

62 where D is outlet pipe diameter [L]. The angle δ_c may be expressed as a function of D and h_c :

63
$$\delta_c = a \cos \left(1 - 2 \frac{h_c}{D} \right) \quad (5)$$

64 Equation 1 links the outflow discharge to the critical water depth in the outflow pipe. We are now
 65 seeking out a relationship between critical water depth (h_c) and the water depth in the tank (h [L],
 66 measured from the invert of the outflow pipe). Knowing the critical water depth (h_c), the critical
 67 energy head H_c [L] can be calculated with the following expression.

68
$$H_c = h_c + \frac{Q_{out}^2}{2gS_c^2} \quad (6)$$

69 The head loss ΔH [L] between the tank and the critical section can be evaluated as a local head loss,
 70 thus:

71
$$\Delta H = K \frac{Q_{out}^2}{2gS_c^2} \quad (7)$$

72 The loss coefficient K [-] was evaluated by CFD using the OpenFOAM software package (2013) for a
 73 100 mm diameter pipe and a flow rate ranging from 0.10 to 1.50 L/s. The conclusion of the numerical
 74 simulations is that the loss coefficient K is approximately 0.4 for the whole discharge range. Using this
 75 value and an estimation of the numerical uncertainty based on a grid sensitivity analysis, the
 76 uncertainty on the outflow discharge (Q_{out}) for a given water depth (h) was evaluated as 5%. Finally,

77 the water depth in the tank (h) can be evaluated using equation 7 (Bernoulli equation written between
78 the critical section and the tank where the velocity head is close to zero).

$$79 \quad h = H_c + \Delta H \quad (8)$$

80 Based on equations 6 and 7, equation 8 can be rewritten as:

$$81 \quad h = h_c + (K + 1) \frac{Q_{out}^2}{2gS_c^2} \quad (9)$$

82 Replacing h_c and S_c in equation (9) by expressions dependent solely on Q_{out} will lead to an expression
83 relating tank water depth (h) to outflow discharge (Q_{out}). However, analytically solving this equation
84 would prove cumbersome due to the sinusoidal functions involved. An alternative solution was found
85 that consisted in rewriting equation 8 into a minimization problem. Incorporating equation (1) into
86 equation (9) implies:

$$87 \quad h = h_c + \frac{K + 1}{2} D_{hc} \quad (10)$$

88 Rewriting equation 10 into the form of an objective function (*obj.fun*) gives:

$$89 \quad obj.fun(h_c) = \left(h - h_c - \frac{K + 1}{2} D_{hc} \right)^2 \quad (11)$$

90 For a given value of h , finding the value of h_c that minimizes the objective function makes it possible
91 to compute the outflow discharge (Q_{out}) using equation 1. Once this relation has been established, it
92 can be associated to the septic tank mass balance equation to build a time-dependent model. For a
93 septic tank, the water mass balance can be written as:

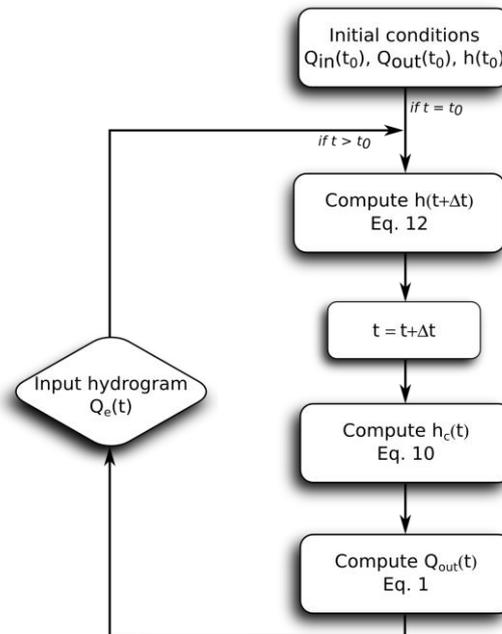
$$94 \quad S \frac{dh}{dt} = Q_{in} - Q_{out} \quad (12)$$

95 where S is horizontal surface of the septic tank at the level of the invert of the outflow pipe [L^2], and
96 Q_{in} is inflow rate [L^3T^{-1}].

97 After an explicit discretization, equation 12 becomes:

$$98 \quad S \frac{h(t + \Delta t) - h(t)}{\Delta t} = Q_{in}(t) - Q_{out}(t) \quad (13)$$

99 The value of $Q_{in}(t)$ is an input while the value of $Q_{out}(t)$ needs to be estimated (except for the initial
100 value). This is carried out by minimizing the objective function (11) at time t . Figure 3 schematizes the
101 basic computation steps.



102

103

Figure 3. Computation steps

104 **Model implementation**

105 The model was implemented in R (R Core Team, 2013). The method used for minimizing the
106 objective function is a combination of golden section search and successive parabolic interpolation
107 (Brent, 1973). Accuracy was set to 1×10^{-10} m.

108 **Practical test cases**

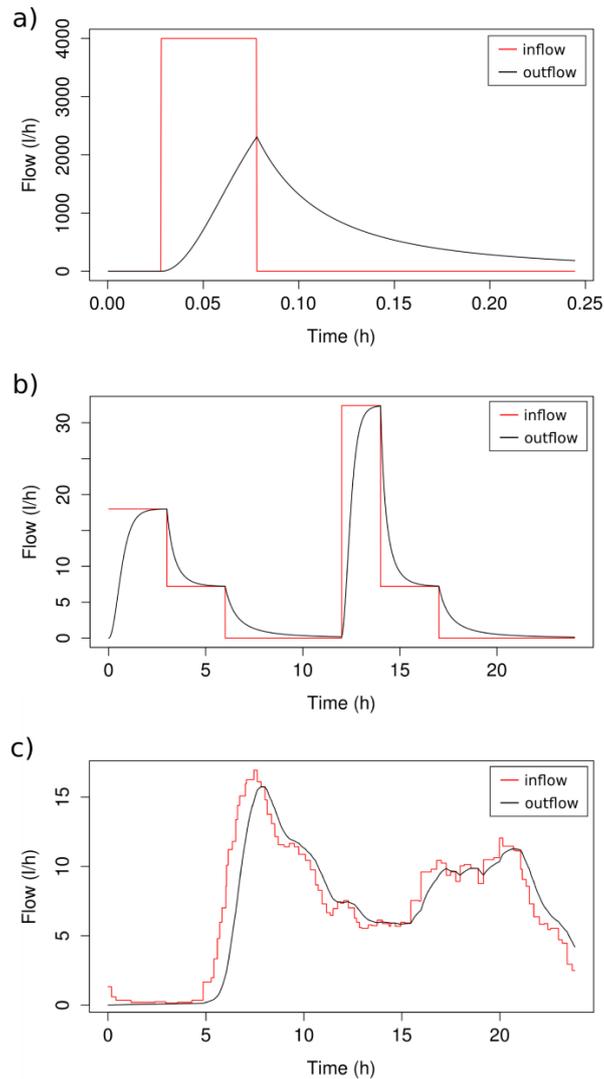
109 This technical note presents three test cases. (1) It is often assumed that the largest inflow rate for a
110 septic tank (if properly disconnected from rainwater) corresponds to the emptying of a bath (200 litres
111 in 3 minutes). (2) In France, new treatment systems require authorization before being
112 commercialized. Since 2009, this authorization is given based on the results of normalized
113 experiments (AFNOR, 2013) carried out by accredited laboratories. Feeding of the wastewater
114 treatment system during these normalized experiments is carried out according to a distribution of the
115 daily hydraulic load that is based on the assumed consumption of a typical household. Based on this
116 distribution, a synthetic hydrograph was generated, corresponding to a two person-household. Daily
117 hydraulic load was estimated at 84 L/pers./day according to Cauchi & Vignolles (2012). (3) Butler &
118 Graham (1995) and Butler & Gatt (1996) presented synthetic hydrographs of wastewater discharge in
119 person-equivalents. Despite the fact that these studies were done on sewage, they are often cited as a
120 benchmark for on-site wastewater treatment systems due to the lack of input hydrographs in this

121 domain (Roland et al., 2009). Here, we used the one presented in Butler and Gatt (1996) as an input in
122 our model. The daily hydrograph was pre-normalized so that daily hydraulic load is the same as in
123 case 2. For all three test cases, the characteristics of the septic tank are the same, i.e. a 4 m² area at the
124 invert of the outflow pipe (100 mm in diameter) that corresponds to a commercial standard.

125 Figure 4 presents the results. A single event, like a bath emptying (case a), is considerably smoothed
126 by the septic tank. The outflow discharge reaches only 57% of the inflow rate at the end of loading.
127 Many treatment systems (e.g. sand filters) downstream of the septic tank have gravity-driven
128 distribution systems and therefore depend on inflow velocity to ensure an even distribution. If the
129 septic tank significantly smoothes its outflow discharge, this could affect the quality of hydraulic
130 distribution in the treatment system. When applied to more averaged hydrographs such as those
131 obtained synthetically based on daily hydraulic load and typical household water usage (AFNOR,
132 2013; case b) or those experimentally observed at sewer level (Butler & Gatt, 1996; case c), the
133 smoothing effect tends to be less significant: mean outflow discharges are only 0.6% and 3.75% lower
134 than mean inflow rates for the second and third test cases, respectively. In these cases, the septic tank
135 only induces a lag in the propagation of the hydrograph. In addition, case b shows that the septic tank
136 may help ensure a better spreading of hydraulic load over the day.

137 Evaluation of septic tank buffering on effluent distribution over the secondary treatment unit would
138 requires better measurements of the inlet hydrograph with a small time resolution. The hydrograph
139 suggested by (AFNOR, 2013) is too averaged and actually presents a shape close to the observed in
140 sewers. Patel et al. (2008) measured outflow at the inlet of gravity distribution devices (after the septic
141 tank) and concluded that the most common flow rates were between 0.0016-2.0.03 l h⁻¹ with peak
142 values up to 0.2 l h⁻¹. For secondary treatments that are not fed by gravity, the septic tank buffer effect
143 may help to ensure a better spreading of the influent over time. Furthermore, the current model could
144 be easily applied to septic tank alternative designs such as tank in series and tank in parallels as they
145 are already widespread in USA and tend to develop in Europe. A sensitivity analysis on parameters *S*
146 and *D* could also indicate which one influence the most buffer effect and lag time.

147 Finally, we would like to stress that not only septic tank induces a buffer effect. Pipes, conducting
148 flow to and out of the septic tank, may also be of importance regarding their diameter (typically 100
149 mm).



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Figure 4. Inflow and outflow hydrographs for three test cases: a) bath emptying, b) synthetic daily dataset, c) dry weather sewage flow (Butler & Gatt, 1996)

153

Conclusions

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We built a simple mechanistic model suitable for modeling the hydraulic buffering induced by a septic tank. The only constant in the model, i.e. the loss coefficient, was calibrated using deterministic CFD modeling. Results highlight significant modulation of flow in single relatively large events such as a bath emptying. However, on smoother hydrographs, such as those currently available for characterizing a household effluent, the flow modulation only adds a lag time into the influent hydrograph. As we progressively gain more knowledge on the actual shape and amplitude of the hydrograph at the inlet of a septic tank, this simple tool could prove be useful for modeling septic tank outflow and its impact on the spread of wastewater over the treatment unit in configurations based on gravity-driven distribution.

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