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Article

Application of On-Site Wastewater Treatment in Ireland and Perspectives on Its Sustainability

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Abstract: The wastewater of one third of Ireland's population is treated on-site using domestic treatment systems (DWWTSs) that usually consist of a septic tank and soil attenuation system. Within the past four years, the legislative framework for these systems has undergone a major change with a registration and inspection regime being introduced to identify legacy sites that will require remediation work, particularly in areas of the country underlain by subsoils of very low permeability. Against this background this study aims to assess the overall sustainability of existing DWWTSs as well as alternative treatment and disposal options. The results show that main CO_{2eq} emissions are from the methane production in septic tanks. The reduced methane production in mechanically aerated secondary treatment systems was found to counterbalance the related emissions due to the additional energy requirements. In contrast, septic tank systems have the lowest construction and operational costs representing the most economically sustainable solution. Pressurised disposal systems are slightly more expensive but have the potential to reduce environmental impact on surface water and reduce greenhouse gas emissions. Clustered decentralised treatment solutions could be environmentally and economically sustainable but ownership, management and related financial and legal issues will need to be addressed and developed.

Keywords: septic tank; on-site wastewater; greenhouse gas; energy; water saving

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1. Introduction

The domestic wastewater of approximately one third of the population in Ireland is treated on-site by domestic wastewater treatment systems (DWWTSs) [1]. A typical DWWTS in rural Ireland consists of a septic tank, providing primary settlement and a limited amount of anaerobic digestion, followed by a soil attenuation system which provides the majority of the treatment while the effluent slowly trickles through the unsaturated soil. Before 1991 the soil attenuation system was traditionally a large pit that was dug into the ground and backfilled with stone or rubble with the effluent being gravity-fed via a single discharge pipe from the septic tank to this so-called soakaway (or soakpit). Since 1991 the construction of a larger percolation area (also known as a leach field, infiltration area or soil treatment unit) became common practice where effluent is split and distributed via parallel subsoil percolation trenches [2]. Sometimes a secondary treatment system (packaged treatment plant) has been installed as an alternative to a septic tank or as an addition to provide aerobic treatment of septic tank effluent prior to discharge to subsoil.

If not situated and constructed correctly, the potential impacts of such on-site effluent are the pollution of groundwater and/or surface water. In particular, areas with inadequate percolation due to low-permeability subsoils and/or insufficient attenuation due to high water tables and shallow subsoils present the greatest challenge in Ireland to dealing with effluent from DWWTSs. If there is insufficient permeability in the subsoil to take the effluent load, ponding and breakout of untreated or partially treated effluent at the surface may occur. This can promote serious health risks as well as the risk of effluent discharge/runoff of pollutants to surface water and also down into wells which lack proper headworks or sanitary grout seals [3]. The nutrient load in the effluent (either as direct discharge or from groundwater baseflow) can contribute to eutrophication in sensitive water bodies, whilst contamination of water sources by human enteric pathogens can promote the outbreak of disease. Alternatively, if the permeability of the subsoil is excessive, the effluent loading on the subsoil too high, or there is an insufficient depth of unsaturated subsoil (e.g., high water table or low depth to bedrock) then the groundwater beneath a percolation area is at risk of pollution, in particular from microbiological pathogens and/or nutrients. It is estimated that the overall proportion of the country with inadequate percolation, which can arise all year round or be intermittent during wet weather conditions, is 39% [4].

A Groundwater Protection Response was developed by the GSI (Geological Survey Ireland) for DWWTSs in 1999 that formed the basis of a relatively new regulatory Code of Practice for Treatment Systems for Single Houses [5] which the Environmental Protection Agency (EPA) has formulated over the past 10 years, with significant input from the findings of EPA sponsored research projects [6]. The Code aims to define subsoil conditions that will provide an acceptable level of treatment for on-site domestic wastewater effluent in order to protect groundwater resources from contamination. The risk assessment based approach is composed of an intensive site assessment procedure, involving a desk study and an on-site trial hole inspection in parallel to falling head percolation tests, which evaluates the suitability of the site and soil for treatment of on-site effluent against the vulnerability of local groundwater resources. The percolation tests are used to determine the so-called T-value (an inverse measure of field saturated hydraulic conductivity and expressed in min/25mm water head loss) and thereby assess the assimilation capacity of the subsoil. For example, the Code specifies a minimum unsaturated subsoil depth of 1.2 m below the invert of the percolation trenches and percolation test results within the range 3 ≤ T ≤ 50 for subsoils receiving septic tank effluent. At very slow subsoil percolation rates, *i.e.*, T > 90 (equivalent to> 0.047 m/day) discharge to ground using typical DWWTSs is not acceptable due to hydraulic limitations. However, on-going research is currently assessing the performance of pressurised distribution systems such as Low Pressure Pipe (LPP) and Drip Distribution (DD) systems as well as Zero-discharge Evapotranspiration systems (using willow trees) in low permeability subsoil settings [7–9]. Based on those results, design guidelines will be produced to augment the current Code of Practice. While licences for effluent discharge to surface water, even after secondary or tertiary treatment, are currently not usually granted for single houses, the EPA and Local Authorities are now starting to consider clustered decentralised treatment solutions with consented surface water discharge. However, the ownership, management and related financial and legal issues still need to be overcome before this will become a more widely accepted solution.

Although the Code of Practice provides guidelines to ensure DWWTSs are situated and designed in a way that water bodies will be sufficiently protected, the European Court of Justice has ruled against Ireland in 2012 in relation to DWWTSs (ref. case C-188/08), finding that the State has failed to adopt the necessary legislation regarding existing on-site systems to comply with Articles 4 and 8 of European Directive 75/442/EEC. Hence, the government has released the Water Services (Amendment) Act, 2012 (S.I. No. 2 of 2012) which requires homeowners with a DWWTS to register and ensure that the system does not constitute a risk to human health or the environment through compliance with standards for the performance and operation of DWWTSs. The Local Authorities are required to establish and maintain a registration system and to undertake inspections to regulate the discharges from these systems while the EPA is the supervisory authority for these inspections. In 2013 the EPA published the National Inspection Plan (NIP) [4] which outlines a risk-based approach for the inspections in prioritizing areas of higher risk to human health and water quality.

In view of the commencement of inspections and upcoming remediation of existing legacy sites this paper assesses and compares the sustainability of existing DWWTSs and considered alternative disposal solutions. According to the US EPA's definition, sustainability creates and maintains the conditions under which humans and nature can exist in productive harmony, that permit fulfilling the social, economic and other requirements of present and future generations. Hence, this paper addresses in a complementary way the three pillars of sustainability and includes environmental, economic as well as social aspects, in order to help in the decision-making process towards more sustainable DWWT in Ireland.

2. On-Site Wastewater Characteristics

The most recent Irish Census carried out by the Central Statistics Office (CSO) Ireland in 2011 revealed that almost 500,000 dwellings are not connected to main sewer networks and thus rely on on-site wastewater treatment systems which equates to more than 1.4 million people (one third of the population). Details about the number of houses and citizens served by the different types of sewerage systems can be found in Table 1 which shows that more than 87% of on-site treatment systems are septic tanks with some form of percolation (either soakaway or percolation area).

Table 1. Results for the type of sewerage system from the Irish Census [1].

Type of sewerage system	Number of private households	Number of citizens
Public scheme	1,092,418	2,871,420
Individual septic tank	437,652	1,276,892
Individual treatment but not septic tank	50,259	166,256
Other type of sewerage	9370	25,158
No sewerage facility	2555	4338
Not stated	57,154	156,505

The Code of Practice states that an average effluent production of 150 Lcd (litres per capita per day) should be used for the design of DWWTSs; this figure assumes no additional influent from rainfall due to illegal connections such as roof downpipes also being connected into the wastewater system. The typical wastewater production from DWWTSs from 18 houses that have closely monitored for periods of up to three years is however only 101.3 Lcd, ranging from 60.3 to 123 Lcd. This higher design figure of 150 Lcd is more associated with water consumption statistics in large conurbations and so lower wastewater production should not be surprising for on-site systems where the inhabitants may spend a considerable portion of their day outside their own single system "catchment". Interestingly on two closely monitored houses where it was known that rainfall from the roofs was directed into the wastewater system, the average wastewater production increased up to 167.8 Lcd. Detailed analysis of the flows coming from DWWTSs (whether septic tanks or more advanced treatment systems) has shown that the average flow to percolation areas is very small (0.5 to 1.5 L/min) which places challenges on distribution of effluent across a percolation area by gravity [10]—a key assumption behind the design methodology in the Code of Practice.

Table 2 shows the typical wastewater concentrations from several closely monitored septic tanks and secondary treatment plants in Ireland over the past 10 years [2,6,7,11]. Note, the secondary treatment plants included in the mean effluent quality data include a variety of different systems used in Ireland from packaged treatment systems such as CAS (conventional activated sludge), SAF (submerged aerated filter), RBC (rotating biological contactor), coconut filter and peat filter as well as systems constructed on site (reed beds and sand filters).

Table 2. Mean effluent quality septic tanks and on-site secondary treatment processes before discharge into the subsoil.

	Septic tank effluent (n = 16)	Secondary treated effluent (n = 12)
COD [mg/L]	580 ± 297	160 ± 72
BOD [mg/L]	365 ± 198	40 ± 22
Total N [mg/L]	128.3 ± 66.2	69.1 ± 42.8
NH_4-N [mg/L]	79.1 ± 47.8	15.7 ± 12.3
NO_3-N [mg/L]	1.9 ± 1.7	26.5 ± 20.8
Org-N [mg/L]	64.3 ± 41.7	18.7 ± 14.6
Ortho-P [mg/L]	18.2 ± 7.7	12.6 ± 10.4
Chloride [mg/L]	134 ± 82.9	99 ± 63
Total coliforms [MPN/100mL] *	$1.78 \times 10^7 \pm 2.7 \times 10^6$	$3.44 \times 10^5 \pm 1.9 \times 10^5$
E. coli [MPN/100mL] *	$2.22 \times 10^6 \pm 2.4 \times 10^5$	$8.43 \times 10^4 \pm 4.7 \times 10^4$

* Total coliforms and *E. coli* results are median concentrations.

3. Environmental Sustainability

The principles of environmental sustainability are for human activities not to be harmful to the environment or depleting natural resources and thereby supporting long-term ecological balance. In this connection the impact of pollutants (organics, nutrients and microorganisms) released by DWWTSs on natural water resources as well as the amount of greenhouse gases emitted due to microbiological processes and from energy use in DWWTSs are estimated. Data used for these estimations were taken from results from previous research projects on pollution load and attenuation of DWWTSs carried out in Ireland within the past 10 years, from international research and from a review about the costs, energy use and performance of available small scale secondary treatment systems in Ireland [12].

3.1. Impact on Groundwater

Research into the attenuation of on-site pollutants from systems constructed according to the Code of Practice passing through a variety of different subsoil types in Ireland have shown excellent attenuation of organics, microorganisms (both indicator bacteria and spiked bacteriophages) and phosphorus (P) in most sites [2,11–14] through just 1 m of unsaturated subsoil. With respect to nitrogen (N), the development of a biomat across the percolation areas receiving secondary treated effluent (SE) was restricted on these sites compared to those sites receiving septic tank effluent (STE) which created a significant difference in terms of the potential nitrogen loading to groundwater (see Table 3). Nitrogen removals have been higher under percolation areas receiving STE compared to SE which has been attributed to the higher organic loading and corresponding biomat development. The average nitrogen removal through unsaturated subsoil receiving STE was 5.27 g/ca.day (grams per capita per day) compared to 1.02 g/ca.day for the subsoil receiving SE. The removal rates have been higher on the more slowly percolating sites and relatively high N loading was found on the septic tank sites discharging effluent into highly permeable subsoil that counteracted any significant denitrification.

Table 3. Average total nitrogen loads through the unsaturated subsoil in six percolation areas in Ireland [12].

	Site 1	**Site 2**	**Site 3**	**Site 4**	**Site 5**	**Site 6**
Treatment	**STE**	**STE**	**STE**	**SE**	**SE**	**SE**
Subsoil field sat. hyd. conductivity—k_{fs} [m/day]	1.05	0.28	0.13	0.84	0.15	0.08
COD loading per trench [g/day]	72.0	40.2	108.4	12.8	14.1	24.5
COD areal load per trench [g/m^2.day] †	14.5	4.47	30.1	71.1	10.4	13.6
Influent total-N to subsoil [g/day]	60.4	28.9	19.6	20.2	18.4	17.8
Areal inf. total-N to subsoil [g/m^2.day] †	2.03	0.81	0.68	28.1	3.41	2.47
Influent total-N per capita to subsoil [g/ca.day]	10.07	7.23	4.90	6.73	3.68	4.45
Total-N per capita after 1m depth of subsoil [g/ca.day]	4.17	1.70	0.53	5.07	3.34	3.40

STE = septic tank effluent, SE = secondary treated effluent; † per unit area of active percolation trench.

These six closely monitored sites were carefully constructed according to the Code of Practice and even distribution across the percolation area was ensured by frequent visits to clean the distribution devices. It must be acknowledged that this is rarely the case for most systems across the country whereby most effluent is likely to be heading down a single percolation pipe due to poor distribution (if indeed a series of percolation pipes has even been installed) which thus overloads that trench/subsoil interface.

The EPA has recently released a Risk-Based Methodology to Assist in the Regulation of Domestic Waste Water Treatment Systems [4]. This assesses the susceptibility of the groundwater to contamination on the basis of the overlying subsoil thickness and permeability, the type of soil (whether wet or dry) and the type of aquifer. For example, it assumes a very high susceptibility with respect to pathogens and phosphorus in areas of high permeability and shallow subsoil depth for 15% of the country. Equally, a very high susceptibility with respect to nitrate loading has been defined for 30% of the country. For each of these susceptibility categories an attenuation factor has then been defined; for example, in the very high susceptibility areas it is assumed that 30% of the effluent load to ground will make its way to groundwater. Given the distribution of susceptibilities and respective attenuation factors assumed as shown in Table 4, this methodology suggests that, on a net national average, 15.5% of pathogens or phosphorus and 16.0% of nitrogen from DWWTS make it through the unsaturated subsoil to groundwater (assuming that there is a uniform density of DWWTSs across the country).

Table 4. Susceptibility of groundwater and surface water to domestic wastewater treatment systems (DWWTS) contamination according to the Environmental Protection Agency (EPA) Risk-Based Methodology [4].

	Percentage land area (%)		
	Groundwater		Surface water
Susceptibility category	Pathogens & MRP	Nitrate	Pathogens, MRP and Nitrate
Low	61.0	67.8	25.8
Moderate	0.00	0.7	25.7
High	23.1	0.0	22.0
Very High	14.6	30.3	25.2
	Fraction of pollutant getting to receptor		
Low	0.00	0.10	0.05 × 0.75
Moderate	0.05	0.15	0.25 × 0.75
High	0.10	0.25	0.50 × 0.75
Very High	0.90	0.30	0.80 × 0.75
% national load getting to receptor	**15.5**	**16.0**	**29.2**

3.2. Impact on Surface Water

The main risks to surface water are in areas of low permeability subsoil (for example, glacial tills) which cannot take on-site effluent loading. The EPA risk methodology discussed previously [4] defines that 39% of the land in Ireland is deemed to have inadequate percolation with respect to on-site wastewater treatment by combining the probability of inadequate percolation in areas designated as both very high and high susceptibility (due to low subsoil permeabilities, high water tables and/or low permeability bedrock). Hence, for these areas surface water is likely to be at a risk from overland flow of ponded on-site effluent, particularly during heavy rain storms. This methodology assumes fairly significant quantities of P, pathogens and N will make their way into surface waters in such areas. For example, in very high susceptibility areas (which account for 25.2% of Ireland) it is assumed that 60% of P, pathogens and nitrogen load from DWWTS will reach the nearest surface water. However, recent results from an ongoing study would suggest that there can still be considerable attenuation in relatively short horizontal pathways from such effluent in higher permeability lenses or ditches before it reaches the rivers [15]. Nevertheless, taking into account the national susceptibility areal percentages and relative attenuations the risk methodology shows overall that 29.2% of the net national pathogens, P and N loads from DWWTSs will reach surface water. Again, this calculation does assume a uniform density of DWWTSs across the country.

3.3. Impact on Greenhouse Gas (GHG) Emissions

3.3.1. Emissions Related to Microbiological Processes

There are three principal greenhouse gases (GHGs) produced by microbial mediated processes related to on-site wastewater treatment: carbon dioxide (CO_2) from both aerobic and anaerobic breakdown of organic matter, methane (CH_4) from the anaerobic breakdown of organic matter and nitrous oxide (N_2O) from the partial denitrification of nitrate. Since CO_2 is considered to be of biogenic origin by the Intergovernmental Panel on Climate Change (IPCC) it is not included as an additional GHG emission and so will not be considered further here. The potential for CH_4 and N_2O production occurs in three distinct areas: in the anaerobic environment of the septic tank (or primary tank of secondary treatment units), in the unsaturated subsoil (vadose zone) and in the saturated zone (*i.e.*, groundwater). It is assumed that no production of either CH_4 or N_2O occurs in the aerobic environment of the aerated secondary treatment chamber of the package plants. The treatment of sludge which is periodically pumped from the DWWTSs and tankered away is dealt with separately in Section 3.4.

There has been little research to date to quantify such emissions from within septic tanks, down through the vadose zone in the percolation areas or through the saturated zone in Ireland or elsewhere. For example, the transformation of N through the unsaturated subsoil is often modelled with denitrification as a single step with N_2 as the end point (e.g., [16] *etc.*). However, a recent study in California by Diaz-Valbuena *et al.* [17] has attempted to measure CO_2, CH_4 and N_2O emission rates in DWWTSs. This estimated an average 11 g CH_4 production per capita per day (as well as 33.3 g CO_2/ca.day) from inside the septic tanks studied. This production rate was noted to be approximately half the IPCC emission rate standard used for septic tanks [18] which uses a methane conversion factor (MCF) of 0.5—their study yielded an equivalent MCF of 0.22. For this study of DWWT emissions in Ireland an average conversion factor of 0.35 has therefore been assumed. The Diaz-Valbuena *et al.* [17] study also determined that the emission of CH_4 from the percolation area was effectively zero and that all the emissions came from the tank. The same study found almost no N_2O was generated in the septic tank but did measure that 0.005 g N_2O/ca.day in the vent pipes connected to the percolation area which was therefore assumed to come from the subsoil. Compared to the average N-removal per capita per day for STE in Ireland of 5.27 g/ca.day (see Table 3) this would suggest that only 0.06% of N removal was due to incomplete denitrification, the rest attributed to full denitrification (to N_2) or possibly via the Anammox removal process. Whilst the progression of denitrification depends strongly on soil moisture conditions, in the absence of any other data this conversion of 0.06% has been used as an average value based on the average N removal statistics given in Table 3 for the STE. It has been assumed that negligible quantities of N_2O are produced in the unsaturated zones receiving SE as studies have shown the nitrate moves down through the soil with very little denitrification [11].

In the saturated zone nitrogen removal is often assumed not to occur unless it passes through certain pyrite rich bedrock types such as shale or impure limestone. In addition, recent studies in a saturated septic tank plumes have suggested that the Anammox process has recently been shown to be a dominant reaction causing the NH_4 attenuation [19] which would compete with any assumptions made concerning N removal via denitrification (whether partial or complete). In other recent studies investigating saturated denitrifying bioreactors using woodchip the production of N_2O from NO_3-N had been relatively low from 0.6% as a stream bed reactor [20] to 3.3% as N_2O-N [21].

Studies of nitrogen transformations through subsoils into aquifers beneath four different agricultural sites in Ireland have recently measured the N_2O emissions from two low permeability (<0.02 m/day) and two high permeability (>0.05 m/day) aquifers. These have shown indirect N_2O emissions via groundwater denitrification accounted for 0.03%–0.12% of N input [22,23]. Hence, in the absence of any more specific data, a value 0.07% of N input being partially denitrified to N_2O has been assumed for this study in the saturated zone as an average value across the country.

The CH_4 and N_2O totals calculated from each process have been converted to CO_{2eq} (carbon dioxide equivalent) using the IPCC recommended global warming potential factors of 25 and 298 for CH_4 and N_2O respectively and quantified on a national basis for Ireland in Section 3.3.3 and Table 5.

3.3.2. Emissions Related to Energy Use

In gravity fed septic tank systems (*i.e.*, septic tank and percolation area) no electricity is used and greenhouse gases are only emitted in relation to microbial processes and during the regular desludging of the system. If a secondary treatment system such as a package treatment plant is used instead of a septic tank or to enhance the effluent quality before discharge into ground energy use can vary depending on the system from 25 kWh/ca.year for media filter to 147 kWh/ca.year for continuously mechanically aerated treatment systems (e.g., SAFs, moving bed bioreactor (MBBRs) and CASs) up to 345 kWh/ca.year for Membrane Bioreactors (MBRs). Applying a conversion factor of 0.562 kg CO_{2eq}/kWh [24], the GHG emissions from these systems range from 14 to 194 kg CO_{2eq}/ca.year. However, it should be noted that there are certain media filters that use gravity and natural ventilation so that no energy is required. At present MBRs haven't been used for single house systems so that the average electricity consumption of packaged treatment plants for single houses in Ireland (incl. SAFs, MBBRs, CASs, sequencing batch reactors (SBRs), RBCs and media filters) is estimated to be 97.23 kWh/ca.year, equating to emissions of 54.64 kg CO_{2eq}/ca.year.

All systems, septic tank and secondary treatment systems, will need regular desludging with GHG emissions related to the diesel used by the tanker (conversion factor of 2.64 kg CO_{2eq}/L). Assuming a diesel usage of 40.6 L/100 km and an average distance of 15 km between the on-site system and the treatment/disposal site, this results in average emissions of 7.76 kg CO_{2eq}/ca.year for annual desludging. However, according to Irish regulations the desludging of a septic tank will only be required once every two to three years. The aspects of sludge treatment and disposal are dealt with in Section 3.4.

For pressurised effluent distribution systems pumps are used to distribute the effluent evenly over the percolation area. Hence, the energy consumption depends on the effluent flow (typically about 0.433 kWh/m^3). With an estimated wastewater production of 150 Lcd the electricity consumption would be about 23.71 kWh/ca.year which equates to annual GHG emissions of 13.32 kg CO_{2eq}/ca. However, it has been shown that the use of water saving devices can significantly reduce a household's wastewater production down to 86.8 Lcd [25] so that reductions in GHG emissions can be expected in relation to the construction and operation of effluent disposal systems. Hence, the electricity consumption related to effluent pumping can be reduced to 13.69 kWh/ca.year saving 5.6 kg CO_{2eq}/ca on annual GHG emissions. At the same time GHG emissions are saved in relation to water treatment and warm water supply. Based on Water UK [26] average company performance values, 0.29 g CO_{2eq} is emitted for every litre of water supplied. Hence, the secondary emission rates for water supply for a person with a water consumption of 150 Lcd is estimated to be 15.88 kg CO_{2eq}/ca.year. With the installation of water saving devices and a reduction of water consumption the carbon emissions could therefore accordingly be reduced by 6.71 kg CO_{2eq}/ca.year. However, the largest savings are obtained from the reduction of warm water use such as during showering and from bathroom taps. It has been shown that 305–421 kWh/ca.year in electricity can be saved when installing flow restricted appliances. Equally, when gas is used as an energy source, 1491.8–2058.5 cf/ca.year (equal to 480–662 kWh/ca.year) can be saved. This equates to carbon emission reductions of 171–236.6 kg CO_{2eq}/ca.year or 99–136.4 kg CO_{2eq}/ca.year, depending on the energy source used to heat domestic water [25].

In summary the energy related emissions for septic tank systems range from 3.88 up to 17.2 kg CO_{2eq}/ca.year comparing a gravity fed system and pumped discharge system respectively. Equally, secondary treatment systems contribute on average with 50.58 up to 63.9 kg CO_{2eq}/ca.year to energy related GHG emissions. Carbon emissions from the energy consumption of centralised wastewater treatment works (WwTWs) in the UK were estimated at 0.41 kg CO_{2eq}/m^3 [26] which yields 22.45 kg CO_2 emissions per person per year when assuming a daily wastewater production of 150 Lcd. While this is less than half of the per capita emissions for the operation of on-site secondary treatment systems, it is significantly higher than the emissions from the standard septic tank systems which represent most of the DWWTSs in Ireland (87%).

3.3.3. Total GHG Emissions

The GHG emissions from both microbiological processes and energy use have been summarised in Table 5 in order to estimate the average total emissions (as CO_{2eq}) for the different DWWTSs. It should be noted that for these estimations it was assumed that only 10% of existing DWWTSs require effluent pumping either due to the site topography or due to high water tables so that effluent needs to be discharged to raised percolation areas. The results show that average GHG emissions from septic tank systems with 164.5 kg CO_{2eq}/ca.year are higher than those from secondary treatment systems which were estimated to be on average 144.0 kg CO_{2eq}/ca.year. Although secondary treatment systems have higher CO_2 emissions related to energy use, due to their predominantly aerobic treatment they release less CH_4 (Table 5) which has been found to contribute largely to the overall GHG emissions (97.6% and 55.4% of CO_{2eq} emissions for septic tank and secondary treatment systems).

Table 5. Mean greenhouse gas (GHG) emissions from the operation of DWWTSs using septic tanks or secondary treatment plants followed by a soil attenuation system.

	CH_4 production [kg/ca.year]	**N_2O production [g/ca.year]**	**Total GHG emissions [kg CO_{2eq}/ca.year]**
Septic tank system			
Septic tank	6.39	0	159.75
Vadose zone	0	1.825	0.544
Groundwater	0	0.876	0.261
Desludging	n/a	n/a	2.59
For pumped effluent distribution*	n/a	n/a	1.33
Total for all septic tank systems in IRL			**164.5**
Secondary treatment plant			
Primary tank of secondary treatment	3.19	0	79.75
Secondary treatment	0	0	54.64
Vadose zone	0	0	0
Groundwater	0	1.581	0.471
Desludging	n/a	n/a	7.76
For pumped effluent distribution*	n/a	n/a	1.33
Total for all secondary systems in IRL			**144.0**

* Only an estimated 10% of systems will have pumped effluent discharge.

From the last Census in 2011 it is known that 1,276,892 citizens are served by septic tank systems and further 166,256 by individual DWWTSs which do not comprise a septic tank. These other individual systems are considered to be packaged secondary treatment systems. Using these figures the total annual GHG emissions related to all DWWTSs in Ireland was estimated to be 233,948 t CO_{2eq} (Table 6) of which 89.8% are related to septic tank systems and 10.2% to packaged secondary treatment systems. Since the majority of the systems (87%) are septic tanks and are based on gravity flow, the emissions related to the systems energy consumption only represent 6.7% of the total GHG emissions from DWWTSs. Hence the microbiological processes especially during the anaerobic digestion (CH_4 production) are responsible for the majority of GHG emissions related to on-site wastewater treatment (Table 6). When seen in relation to Ireland's GHG emissions of 57.92 Mt CO_{2eq} in 2012 (EPA press release on www.epa.ie) DWWTSs account for 0.4% of the country's emissions.

Table 6. Estimated GHG emissions in connection with all DWWTSs in Ireland.

	Emissions from microbiol. processes [t CO_{2eq}/year]	**Emissions from energy use [t CO_{2eq}/year]**	**Total emissions [t CO_{2eq}/year]**
Septic tank systems	205,011	5,004	210,015
Secondary treatment systems	13,337	10,596	23,933
Total DWWTS	218,348	15,600	233,948

3.4. Sludge

There are little national data on the quantities of sludge collected from DWWTSs and where it ends up although a report is imminent from the Environmental Protection Agency on this issue in response to the predicted increase in DWWTS desludging that will occur following the implementation of the National Inspection Plan. Ideally, the accumulated solids in the septic tank should be desludged once every two to three years and taken by tanker to the inlet works of municipal WwTWs. Here, the solids should mainly settle in the primary tanks and then undergo further treatment with the rest of the sludge at the works. However, anecdotally it is known that a lot of the septic tanks across the country are desludged by local farmers who then spread the waste onto their land as a fertiliser. Studies on septic tanks in temperate climates have shown average accumulation rates of sludge of between 0.18 to 0.34 L/ca.day within the tank, with rates typically higher in the first year and dropping thereafter [27–29]. Using 0.25 L/ca.day with the population served by septic tanks in Ireland would equate to an annual sludge production of 2854 t/year, assuming the concentration of sludge in the tanks is 24,500 mg/L [30]. For the packaged treatment systems, sludge is produced both in the primary sedimentation tanks and after the aerated secondary treatment stage. Due to their smaller volumes these units would need to be desludged every year. The annual sludge production in the primary tanks from these units equates to 303 t/year. For the secondary treatment sludge the solids assuming an average BOD removal of 325 mg/L (see Table 3) and taking a yield factor of 0.5 as an average across several different secondary treatment process types, equates to an annual sludge production of 14.6 t/year Hence, an estimate of the annual national total of on-site wastewater sludge production is 3172 tonnes of solids which theoretically could end up in the sludge treatment of WwTWs. This compares to approximately 85,000 tonnes of sludge generated by the WwTWs [31], most of which ends up on agricultural land. Many of the larger WwTWs in Ireland now use anaerobic digestion as the main sludge treatment process and collect the resulting biogas (CH_4 and CO_2) for use in a combined heat and power (CHP) plants. The IPCC CH_4 production rate for anaerobic treatment of sludge is 2 g CH_4/kg solids treated; N_2O production is assumed to be negligible. If the recovered gas is used for energy production in a CHP, then the resulting greenhouse gas emissions from the combustion of the gas are not significant, as the CO_2 emissions are of biogenic origin, and the CH_4 and N_2O emissions are very small. However, several WwTWs have stopped using their anaerobic digestion units and linked CHPs over the last couple of years due to process problems and associated costs and have instead been merely thickening the sludge and sending it to landfill, forestry or land reclamation where it requires a lesser form of treatment. Given that it is unclear where the sludge from DWWTSs ends up and then the form of treatment it receives, it is not possible to estimate the national average net GHG emissions associated with this aspect at present in Ireland.

4. Economic Sustainability

Economic sustainability is regarded as the use of various strategies for employing existing resources to their best advantage so that a responsible and beneficial balance can be achieved over the longer term. In order to be able to identify the most cost-efficient strategies for DWWT and considered remediation options for existing failing systems, capital and operational costs have been estimated using experience and prices obtained from the construction of these systems in Ireland. Furthermore, data from reviews on water saving devices [24] and about the costs, energy use and performance of available small scale secondary treatment systems [12] has been used to assess the improvement of economic feasibility for different DWWTSs depending on management strategies involving a targeted reduction in wastewater production and the clustering of houses with DWWTSs.

Table 7 shows estimations of per capita construction and operational costs for various DWWTSs that are used in Ireland or are currently considered to find application in areas with inadequate percolation. Costs are calculated for a single house system serving three inhabitants but it should be noted that per capita costs usually decrease if the houses' occupancy rate is higher. Construction costs include material and labour and annual operation costs include electricity, desludging as well as the maintenance of the systems. Table 7 also shows how the construction and operational costs would reduce if some relatively simple water saving devices were installed into a house, dual-flush toilet, low flow shower heads and tap aerators. A standard septic tank system with gravity fed percolation trenches costs about €1132 per person which increases to €1605 where a packaged treatment plant is installed in place of a septic tank. For systems that require a pumped effluent discharge a pump sump including the submersible effluent pump will need to be added which increases per capita costs by around €230. For the LPP (low pressure pipe) and DD (drip distribution) pressurised distribution systems it is recommended that secondary treated effluent is received to avoid clogging, so packaged treatment systems have been assumed for these alternative dispersal systems. The construction costs of an LPP system are comparable with a secondary treatment system including a standard percolation area. However, the DD system with a per capita cost of €2340 is significantly more expensive which is due to the additional control panel for the timed dosing regime and due to added costs from filters and headworks required for the system. Zero-discharge Evapotranspiration systems are very expensive (€5300 per capita) due to their size. Large basin volumes are needed to hold the wastewater during the winter months where evapotranspiration is at a minimum. This requires intense excavation and a large impermeable liner which are major cost factors in the construction of these systems. Their design is strongly influenced by the daily wastewater production so that a reduction of the household's water use by installing water saving appliances will reduce the system size and hence its construction cost. Calculations have shown that material and construction costs for an evapotranspiration system using willow trees will be 36% lower than for a standard sized system (Table 7). These cost savings are mainly due to the decreased use of the expensive liner as well as a significant reduction in the construction time (for excavations) and hence labour costs. In comparison, for LPP and DD systems the size does not significantly affect the construction time so that construction costs are only reduced by up to 4% and 8% respectively (Table 7).

Beside the estimated construction costs Table 7 also shows operational costs for the different disposal options based on standard and reduced wastewater productions due to water saving devices. Systems comprising a septic tank and a gravity fed disposal system have the lowest annual operational costs of €22/ca for desludging of the tank (every three years). For systems that rely on a packaged secondary treatment system the costs further include electricity for aeration or/and effluent pumping as well as annual servicing charges which increases the average annual running costs to €135/ca. Pressurised distribution systems then add another €4 /ca per year for the pumped effluent distribution, however, this can be reduced to €2.50 if the wastewater flow is reduced due to water saving devices.

While water saving does not affect the construction costs of a wastewater storage tank, it greatly reduces (42%) the emptying frequency and hence annual operation costs related with this disposal method (Table 7). However, it should be noted that the use of a cesspool will only be economically feasible for holiday houses that are occupied only during parts of the year. The costs presented in this paper are estimates for a holiday house with an average occupation time of 17 weeks per year.

Table 7. Estimated per capita construction and operational costs (excl. value added tax (VAT)), for domestic wastewater treatment systems in Ireland. Costs are based on a system serving three inhabitants and being sized according to a standard and reduced wastewater production.

Construction costs	Standard wastewater production (150 Lcd)	Reduced wastewater production (86.6 Lcd)
Septic tank with percolation area	€1132	n/a
Packaged secondary treatment system with percolation area	€1605	n/a
Low pressure pipe system †	€1671	€1609
Drip distribution system †	€2340	€2166
Zero-discharge Evapotranspiration system	€5300	€3400
Cesspool *	€1200	€1200
Annual operational costs *		
Septic tank with percolation area	€22	€22
Packaged secondary treatment system with percolation area	€135	€135
Low pressure pipe system †	€139	€137.50
Drip distribution system †	€139	€137.50
Zero-discharge Evapotranspiration systems	€22	€22
Cesspool *	€714	€412

* Only considered for holiday homes; costs are based on an average occupation time of 17 weeks per year; † systems include a packaged secondary treatment system.

Water saving actions will not only reduce the construction and operational costs of on-site disposal systems but also lower the households' utility bills for water and energy. Based on a volumetric water charge of €0.75/m^3 for rural areas in Ireland [32] the estimated annual water cost savings are up to €17.36/ca when using water saving devices. At the same time, appliances such as flow restricted shower heads and tap aerators that reduce the consumption of warm water will also promote a reduction in energy used to heat water for domestic use. Based on the estimated water use reduction of up to 42% it was estimated that up to €73/ca.year and €32/ca.year can be saved where water is heated using electricity and gas respectively [25]. When operational costs are expressed as net costs and incorporate annual water and energy cost savings (€49 or €90/ca.year) operational costs for DD and LPP systems can be reduced by 36% up to 68%. The generally low running costs for the evapotranspiration based willow system pay back completely by the annual savings made through water and energy savings.

Analyses for Ireland show that in areas of relatively dense settlement it could be economically feasible to connect single houses via a small bore sewer system and treat the wastewater at a decentralised plant before consented discharge to a nearby watercourse. The cost analyses carried out for packaged secondary treatment systems [12] have shown that for a single house system serving three up to six inhabitants the average per capita costs range from €450–€900 for CASs, SAFs and SBRs up to €1800–€2000 for MBRs (Table 8). Generally a decrease in capital costs results when larger models are used to serve small communities (≥20 PE) and with economies of scale per person realised (Table 8). For example, the cost per person for a SAF system is reduced by 50 up to 75% for a plant serving more than 20 people compared to a single house system serving three to six people.

For a single household the annual electricity costs for SAF, MBBR and CAS systems is estimated to range on average between €20 and €30 /ca (Table 8). Due to the energy intensive membrane filtration process, running costs of MBRs can be about twice as high. In some filter media systems the effluent is distributed by gravity so that no electricity is needed. Other systems however use a pump with float switch to apply the effluent intermittently over the media. The arising electricity costs to run these pumps are below €5 /ca.year. As the pump operates depending on the wastewater production per capita costs are expected to stay similar for larger systems. The SBRs are considered an energy efficient technology as treatment cycles are only started when enough wastewater has been collected in the primary chamber. Observed electricity consumptions during the European testing according to EN 12566-3 have shown that the annual running costs for small SBR plants (up to 8 PE) will range between €4 and €6.60/ca which is expected to stay fairly constant with increasing system size. However, as for the capital costs, for most of the treatment processes, there are economies of scale with respect to per capita operational electricity costs. For an MBBR system for instance running costs can fall from €20 below €10/ca.year (Table 8).

Table 8. Average per capita capital and annual electricity costs for single house and small decentralised packaged treatment systems in Ireland [12].

Treatment systems	Single house system costs [1] [€/ca]		Small decentralised system costs [2] [€/ca]	
	Capital	Operational	Capital	Operational
MBR	1800–2000	50–70	600–1200	<30
MBBR	1500	20–30	600–800	<10
Filter media	840–1200	0–5	350–700	0–5
SBR	620–900	4–7	300–500	4–7
SAF	475–840	20–30	150–250	<18
CAS	540–600	20–30	250–450	<15
RBC	n/a	16	420–600	<5

MBR = Membrane Bioreactor; MBBR = Moving Bed Bioreactor; SBR = Sequencing Batch Reactor; SAF = Submerged Aerated Filter; CAS = Conventional Activated Sludge; RBC = Rotating Biological Contactor; [1] based on a single house system serving 3 to 6 inhabitants; [2] serving small communities ≥ 20 PE.

5. Social Sustainability

Social sustainability is the ability of a community to develop processes and structures which not only meet the needs of its current members but also support the ability of future generations to maintain a healthy community. In order to address the present social sustainability of DWWT in Ireland, existing problems and recent developments concerning aspects of social equity, social justice, social support and health equity will be discussed.

This is an interesting and important time with respect to on-site wastewater treatment in Ireland, as it has never been higher on the political agenda as well as in the public's consciousness. The registration of all the systems and the subsequent inspections that are being rolled out across the country according to the National Inspection Plan (the Government's response to the EC prosecution detailed earlier) have focused the minds of rural dwellers on their DWWTSs which up to now have generally received little attention. The aim of the National Inspection Plan to inspect all existing (so called legacy) systems as well as the tightening of the regulations with respect to the permeability of the subsoil in the new Code of Practice has led to much debate with respect to Rural Planning such as the rights and responsibilities of those who wish to live in the countryside. For example, at present most people in Ireland do not pay explicitly for water (or wastewater treatment) rather it is funded by the government from general taxation. This has brought criticism of the new inspection regime by rural dwellers saying that they are effectively paying twice for wastewater (*i.e.*, for the provision of water and wastewater treatment in urban areas as well as their own DWWTSs). However, as part of the economic bailout programme agreed for the country with the EU-ECB-IMF, the government has just transferred responsibility for water services provision and wastewater treatment from the 34 Local Authorities to one national semi-state company, Irish Water and will introduce domestic water charges. The installation of water meters has now started and water charging will start across the country in 2015. The new water charge will also cover wastewater treatment and so has the potential to bring some equity for the on-site wastewater treatment sector. This new development offers an opportunity to partition the water bill into water supply and wastewater treatment as occurs in some other European countries (e.g., Denmark) which could allow further discretion to rebalance the perceived divide, although this is not been decided yet by Irish Water.

It is clear that the inspections will find many older legacy systems to be inadequate but there is still a question as to the level to which they will be required to be upgraded and whether grants will be available. For many existing sites it may not be possible to find an appropriate solution based upon the Code of Practice standards due to on-site restrictions and/or financial considerations. For example, many houses will be located on sites with very low subsoil permeability and high water tables which would be deemed unsuitable as a new planning application according to the Code. Hence, guidance will need to be given as to best practicable upgrade in such situations (with or without grants) in order to protect the environment and public health, even though it might not conform to the optimum design solutions as defined currently in the legislative Code of Practice. As discussed in Section 3.4, there are also concerns over the predicted volume of sludge disposal which should be periodically tankered to wastewater treatment plants. At present many people do not desludge their septic tanks at anything like the required frequencies and much of the sludge that is collected is known to be taken unofficially by local farmers to be spread on their land.

Despite the burgeoning public interest in on-site wastewater treatment, a recent survey of homeowners across the country [33] revealed a number of significant knowledge gaps which currently exist among DWWTS users in Ireland. Hence, future engagement strategies are needed to provide guidance regarding the role of people and their activities within the hydrological cycle to decrease the human health and environmental contamination burden posed by on-site systems. For example, recent water quality statistics [34] for 2012 have revealed a significant increase in the number of Verotoxigenic *E. coli* (VTEC) infections in Ireland with its second most common transmission route reported to be via waterborne transmission with inherent links to private wells. This was particularly linked to the increased rainfall during the summer of 2012 with the obvious rural sources of contamination being agricultural activities and on-site wastewater treatment systems. Indeed, research in Ireland investigating the water quality in over 200 private wells [3], found a higher susceptibility for contamination for those wells located in the Low vulnerability area (compared to High and Extreme vulnerability) which was attributed to greater surface runoff in those areas leading to the entry of surface or near surface pollutant from septic tanks and agricultural sources into wells which lack proper headworks or sanitary grout seals. Hence, although the vulnerability class is a useful criterion for the protection of the groundwater resource beneath different subsoils, it may not on its own be a reliable indicator as to the likelihood of contamination in the private wells themselves.

6. Discussion and Conclusions

An attempt has been made in this paper to assess the sustainability of on-site systems during a very interesting period in Ireland's history regarding water provision and on-site wastewater treatment. Whilst further studies are needed in some areas to provide more accurate national statistics (for example, GHG emissions in the vadose zone), this is a first step to providing a more complete comparison between different options available for the treatment of on-site wastewater in an Irish context. For example, it is noticeable that the main GHG emission in terms of CO_{2eq} is from the methane production within the anaerobic environment of the septic tank. This raises questions such as could these emissions be captured and used as a biogas in the future, or should the use of secondary treatment systems be promoted even though they usually require ongoing energy inputs.

In general, systems granted planning permission and built according to the new Code of Practice should provide adequate treatment to both groundwater and surface water, as long as they receive regular maintenance. This has raised some concerns in relation to whether the WwTWs have the capacity to take the sludge from on-site systems if all of them are being desludged at the required frequency and not being spread on land.

Now that the national inspection campaign has started, the most pressing issue is what to do with failing legacy sites particularly those in low permeability areas with high water tables. The rationale of the inspections ultimately is to lower the environmental impacts to waters and protect public health, tenets which must be kept in mind as proposed solutions will inevitably come up against financial and physical site constraints. Alternative on-site treatment options are now being researched as possible solutions in areas of low subsoil permeability, for example the use of pressurised distribution systems (LPP and DD) which would improve environmental sustainability in terms of reduced surface water impact and also slightly reduce GHG emissions with respect to a conventional septic tank. The installation of relatively modest water saving technologies (dual flush toilets, low flow shower heads *etc*.) will also reduce the size of these system's percolation areas required which increases their applicability for legacy sites where spaces can be limited and will reduce a rural household's GHG emissions even further. The benefits of reducing water consumption have also been clearly shown from a financial perspective to the individual householder. Hence, LPP and DD could be an environmentally sustainable solution but they are more expensive to construct and to run (compared to standard septic tank system).

Other on-site solutions being considered for low permeability areas are zero discharge evapotranspiration systems using willow trees in a lined basin and closed tank cesspools. The evapotranspiration systems are expensive to construct and require a large surface area and it is still not clear whether they can actual perform as zero discharge systems in the Irish climate. Cesspools are not really economically sustainable for houses with full time residency, although may have a role where a house is fitted with water saving appliances and is used as a holiday home for example. There are also now opportunities to consider more passive systems and trial ecosanitation technologies which target recycling of the wastewater resource using for example urine separation and/or composting toilets.

At a more strategic level the concept of clustered decentralised systems has potential both from an environmental and economic sustainability perspective. Hence, it is clear that moving forward the Local Authorities and the new national water authority Irish Water can take a more strategic view of wastewater treatment for rural housing to consider different solutions such as group sewerage schemes. This has happened to a greater extent with the provision of water in Ireland with nowadays only approximately 13% of the Irish population (~212,000 households) left that are obtaining their water supply from private wells, the rest being provided with potable water by some form of mains or group water provision [1]. To this end a GIS modelling tool is being developed for the Local Authorities as a decision support tool to investigate options such as the clustering of several houses [35]. The legal, social and economic aspect of the ownership of such clustered wastewater infrastructure will need to be addressed and developed however and perhaps much can be gained from the experience of the group water schemes throughout Ireland.

Finally, the EU Water Framework Directive requires all sources of pollution to be categorised and programmes of measures developed on a river catchment basis. Hence, the relative contribution of pollutants from DWWTSs to both surface water and groundwater with respect to other sources (mainly agricultural sources) needs to be quantified. This is also pertinent with respect to the government's Food Harvest 2020 strategic plan [36] which calls for an intensification of agriculture for an increase in primary production of 33% by the year 2020. There is little evidence in Ireland or worldwide to show that on catchment basis DWWTSs are anything more than a very minor contributor to nutrient loading, but at a local scale can be an issue, particularly with respect to public health regarding private wells. DWWTSs are thought to have an impact on surface waters in some geologic settings. For example, work on Irish catchments using high resolution phosphorus monitoring in small headwater rivers [37] has inferred that higher levels of P at low flow conditions can be attributed to on-site systems and can have a disproportionate impact at such times, although still relatively minor. Equally, other research in the UK [38] has shown high impact from septic tank effluent on small streams in a heavy clay catchment, again particularly during low flow conditions.

In summary, on-site wastewater treatment has never been so high in the public consciousness and so there is a real opportunity to change the relationship that rural dwellers have with their systems to understand the principles and take more care with them going forward in terms of protecting both public health and the environment. This also provides an opportunity for more strategic thinking as to the mechanisms of treatment and disposal of on-site effluent for both existing systems and also future planning decisions and the different impacts upon the sustainability of such systems.

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Author Contributions

The two co-authors contributed equally to this work. Both authors read and approved the final manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

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