Enabling sustainability in the wastewater industry by finding space for primary adopters: Part I – mass balance and microbial kinetic linkages to individual variability.

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1 Introduction

Primary adopters are those individuals within a population that adopt new technologies first.

They have an important role in sustainability as these individuals will be the first to adopt the more sustainable technologies. Others then follow their lead. The case for the primary adopter is based on two parts in this paper: first,

- It is shown, using nutrient capture technologies and mass balance laws, that an environmental impact of zero[1] is possible if 100% of the population adopts nutrient capturing technologies. This is better than can be achieved with a centralised sewerage system as it could be done while also minimising the use of energy and water. Full recycling of nutrients would require transport to food production systems, but the initial recovery of the nutrients from the 'waste' is possible with zero energy.
- The primary adopter **begins** this path to zero environmental impact.

Second,

- The use of a simple first-order microbial kinetic that is 'calibrated' to actual data is shown to capture important behavioural characteristics of a water-based system. A person (or dwelling) adopting sustainable technologies has a deterministic effect on a centralised treatment station. The effects of changing the quantity of commonly used design parameters: volumes, BOD_5 and nutrients; are explored. This can form the **logic** on which to base the beneficial impact of the primary adopter. Mechanisms, such as economic linkages, attach very easily to this logic.

The development of nutrient capturing technologies and the signals society gives commerce of their need are other aspects of social change towards more sustainable technologies that are a part of this series of papers. However, this paper confines itself to identifying those mass balance and microbial kinetic linkages that can then be used by these other parts of the wider issue.

2 The case for the primary adopter

There is a natural variability within a population in terms of an individual's willingness to adopt new technologies. These characteristics are well understood by those trained in marketing, but a particularly useful attribute for the development and use of sustainable technologies is the role of the *primary adopter* in effecting social change (Rogers, 1995). Primary adopters are those individuals

[1] Zero is a useful concept as it necessitates consideration of the case for **any** use of resources. For example cleaning of a toilet would use water but is it possible to have a design that requires no cleaning – a cat hole in the forest for example puts all the nutrients into the biosphere, yet the spade does not need cleaning after use.

who adopt new technologies long before the general population is ready to and provide an example of what is possible.

The primary adopters should be nurtured for their role in moving society towards sustainability, especially in an industry whose governing act necessitates sustainability. To find space for primary adopters, individual variability needs to be accommodated; or at the very least not all individuals should be treated the same until the variability is shown to be insignificant.

Given that these individuals can have a useful role in social change, then two questions arise: first; is the magnitude of the potential change within the waste water industry sufficient to seek ways of accommodating them and second, how can this value be harnessed? Both these are covered in this paper:

- The magnitude of the potential change is addressed by the use of mass balance laws (Section 3).
- Mechanisms enabling primary adopters to consider choosing these different technologies from within the dominant technology of centralised sewerage are discussed using microbial kinetics (Section 4).

3 Enabling the variability to express – the value of mass balance

To enable individual variability to express a mass balance approach is convenient as mass can be measured at the scale of the individual but also has access to the very core of the sustainability question. The path of each atom while under human influence can be traced and its point of exiting human influence (particularly our technologies) is the assessment point for environmental impacts. With the added advantage that atoms also enable linkages to energy and nutrients, which are also components of the sustainability question.

What we think of as a quantity of polluted water (called sewage) can be further divided into a number of separate sources using mass balance: Equation 1.

Equation 1

$$Sewage_n = \sum_{i=1}^{i=n} (greywater_i + faeces_i + urine_i)$$

Where n is the number of people for which the sewerage scheme is being designed and greywater, faeces and urine have many different components for which: volume, pathogens, and the chemical components: nutrients and carbon; are the most relevant for sustainability purposes.

There are two sources of variability in Equation 1:

- Differences between waste streams (greywater, faeces, urine). The implications of which are explored in Chapman (2014a).
- Variability between individuals ($\sum_{i=1}^{i=n}()$); the subject of this paper.

Any attributes of this variability that can help humans move towards sustainability need to be firstly, identified and secondly, used if they are to make a difference.

3.1 The magnitude of the potential of primary adopters

This is a task particularly well suited to a mass balance analysis using Equation 1.

An analysis could be done on any of the components of the waste stream, but as nutrients (particularly nitrogen) are driving the Glenorchy sewerage system, then this is used to illustrate the behaviour of the system when individual variability is allowed to express. If most individuals in a population of (n) contribute a quantity of nitrogen (N_j) to the sewage stream but a proportion (a) of this population behave differently and only contribute N_p to the sewage (which includes the possibility of zero contributions), then Equation 1 can be written as:

Equation 2

$$N_n = \sum_{i=1}^{i=(n-an)} \left(N_{j\,(i)}\right) + \sum_{i=(n-an)}^{i=n} \left(N_{p\,(i)}\right)$$

As measuring each individual requires considerable effort, there is computational convenience (and little loss of precision) if we treat the population as two averages: N_j & N_p - see Chapman (2015b) for an equation to determine these averages. Using average values Equation 2 reduces to:

Equation 3

$$N_n = (n - an) \times N_j + an \times N_p$$

Equation 3 returns a linear relationship between the proportion of the population adopting nutrient recycling technologies and the total nitrogen load to the environment that **includes the possibility of zero environmental contributions** if a = 1 (Figure 1).

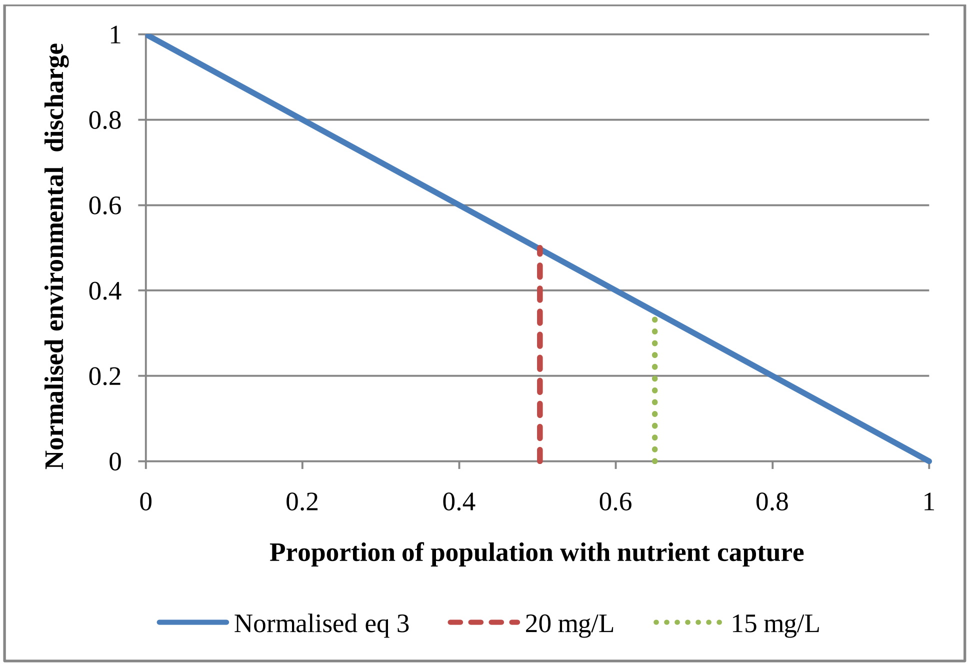

Figure 1 – The effect of a changing proportion of the population using nutrient capturing technologies on the normalised environmental load. The two points (20 & 15 mg/L) are discussed in Section 3.3 below. Note the 20 mg/L discharge level is that for which consent is being obtained for the proposed Glenorchy sewerage scheme. By comparison, if 65% of the population adopted nutrient recycling technologies then the net environmental discharges would equate to 15 mg/L; considerably better than the proposed system.

3.2 Releasing the potential

Given that nutrient capture has the **potential** to reach zero environmental discharges, then how to release this potential becomes the next constraint to implementing the development of technologies that contain this potential. Beginning the nutrient capture question pre-technology (that is, mass balance analysis is applied to urine, faeces and greywater separately) enables an objective assessment of the preferred *collection* and *transport* systems as these can be specific to each of the sources of nutrients. A single end-of-pipe solution can be compared with multiple on-site systems (urine separating toilet bowels for example) using the other sustainability requirements: zero energy, zero water and zero pathogens (see Chapman (2014a) for further discussion on this point). If compromises are required in terms of technology development, at least their resolution will be based on the objectivity inherent in the original mass balance approach to the question.

The other side of the development of sustainable technologies are the social processes by which decisions are made in favour of these technologies, and this includes the incentives for commerce to develop and manufacture such technologies. The primary adopter has an important role here as they occur at the extreme left hand edge of the effect noted in Figure 1. Their potential **effect** in terms of social change is that the proportion of the population with nutrient capture (a in Equation 3) increases from the primary adopter's point of a = 1/n; they are the trigger for the **beginning** of the path that has the potential to lead to zero environmental discharges. The effects on the environmental discharge arise from the cumulative effects of the changes that they **initiate** rather than the magnitude of their individual contribution. This is a function of social processes rather than technological innovation, although the technology availability is a component of the 'information realm' of the primary adopter (discussed further in Chapman (2015a).

The potential apparent in Figure 1 begins with only a few primary adopters, but it is only as these technologies become more widespread that the potential of nutrient capture actually manifests. Creating the 'space' for primary adopters is very important because of the 'trajectory' towards sustainability that they carry, rather than the size of their individual contribution.

3.3 A useful breakeven point

If the only technology being used were nutrient capturing technologies (that is, there was no treatment station at the end of the pipe) then there will be a breakeven point beyond which it is better to encourage nutrient capture technologies, rather than this being a function of the sewerage treatment station. To find this breakeven point, the RHS of Equation 3 has two components: the general population (N_j) and those acting differently (N_p). The relationship between them (a) needs its value to be determined for this breakeven point.

Simplify Equation 3 by assuming nutrient recycling technologies contribute zero N to the environment ($N_p = 0$) and rearrange to determine (a) at the breakeven point:

Equation 4

$$a = 1 - \frac{N_{conventional}}{N_j \times n}$$

To compare nutrient capture with centralised treatment, then $N_{conventional}$ is the regulatory discharge standards. Solving for (a) gives the proportion of the population that needs to adopt nutrient capturing technologies for which the whole system would be as good as a conventional sewerage treatment station – even if the N_j's had no treatment (direct discharge).

For the proposed Glenorchy sewerage system the discharge standards are 20 mg L^{-1} (this is $N_{conventional}$ in Equation 4). Design flows are 760 L $dwelling^{-1}$ d^{-1} from 3 people. Each dwelling therefore adds 20*760/1000 = 15.2 g N d^{-1} to the environment. For the divisor of Equation 4, each person produces 4 kg N per year or 10.9 gm d^{-1} (WHO, 2006, p. 9) and n = 3 people per dwelling.

The breakeven point for this set of data using Equation 4 with the values: $N_{conventional}$ = 15.2; N_j = 10.9; n=3; is a = 0.503. This means that if 50.3% of the residents fitted N capturing technologies (for which their N discharges to the environment are assumed to be zero) while the other 49.7% discharged all their N to the environment **without any treatment** then the total N load to the environment is the same as what would be achieved with the proposed centralised treatment station.

By comparison, a more stringent discharge standard of 15 mg L^{-1} with the same design flow (760 L $dwelling^{-1}$ d^{-1} from 3 people) resulting in a daily discharge of 11.4 g N d^{-1}. The breakeven point for this is 65.1% adopting nutrient recycle.

These breakeven points are only locations on a continuum that are convenient for administrators of our governing Acts, but they are not the only way of behaving. Increasing the proportion of residents with nutrient capture over time will result in a decreasing environmental impact over time and this can be achieved with non-coercive methods. These non-coercive methods can sit alongside the coercive ones.

3.4 Finding alternatives to treatment station upgrades

An alternative use for Equation 3 is to gather data on **preventing** the need for sewerage treatment station upgrades. In this case $N_{conventional}$ = constant; while n increases as the population grows. The proportion of the population needing to move towards nutrient capture ((a) - which is not confined to new connections) can be determined.

Mass balance is not the only consideration in this as there are design impacts on treatment stations arising from changes in BOD_5, volume changes and C:N ratios (discussed in Section 4 below) but the principle remains.

The location of these new technologies can be anywhere within the treatment station catchment area. This is beneficial as forcing a different technology onto *new* connections necessitates the exercise of power with its attendant resentment as some individuals will not be willing to use such technologies.

An alternative that would speak to primary adopters is to use the unit upgrade cost of the treatment station ($/ kg N for example) as an incentive for individuals who wish to purchase nutrient capturing technologies. These individuals needn’t be confined to new connections and no legislative power needs to be exercised. It is a low cost administrative strategy as it would require only a single on-site inspection to ensure that nutrient capturing technologies are fitted. Motivation can be based instead on a reward, which is after all how we teach our children; we have a brain structure that responds to these incentives.

4 Linking individual variability with centralised treatment using microbial kinetics

Using the notion of the emergence of combined parameters (Chapman, 2009) a very simple model can be calibrated using measured performance data. In cutting out much of the complexity a simple model can give insights into behaviour patterns of the system that apply to other socio-economic situations.

Such a model can only be used within severely constrained limits, being specific to the particular technology and conditions of its use, but this state enables the more useful characteristics to become visible as the significant underlying interconnections are retained. This attribute is used extensively in this section to extract socially useful information from Nature's complexity.

The case for using such a simple model can be argued to be valid by consideration of the derivation of the rate constant. The rate constant measures the relationship between the microbial world and chemistry (organic matter) – its value is determined experimentally. Each chemical compound/type of microbe will have a specific rate constant, but this level of complexity is inaccessible to any technology whose inputs contain a wide range of chemical compounds and develops a complex micro-fauna. The manner of determining the rate constant can therefore be changed depending on the model's purpose. Chapman (2008) for example separated the electron acceptors into two as he wanted information on odour generation which primarily occurs within non-oxygenated parts of a composting particle, but separated the substrates into three as he needed precision over longer timeframes. Three substrates with 2 electron acceptors results in 6 different rate constants that makes the model spatially complex. This level of complexity is useful for insights into a technology detail but not very useful for social insights. A single rate constant for the same system would therefore be net of a mix of 6 combinations of different substrates and electron acceptors and consequently not very useful for insights into refining the technology design, but enables insights into the patterns of behaviour that are of interest for this paper.

In effect this is trading precision for greater insights into useful considerations.

To get insights into the effect on treatment station design of individual variability arising from some individuals choosing nutrient recycling, and/or BOD_5 and/or water reduction technologies, it is convenient to use a first-order microbial kinetic that links chemistry with the biosphere. This first-order derivation is simple and widely used. Although it may not be precise at low concentrations, nor reflect the *actual* complexity of the system, it is sufficient for 'seeing' the useful patterns of behaviour of the system. For a substrate (S) in a system with a rate constant (k), then the behaviour over time (t) can be described by:

Equation 5

$$S_t = S_0 \times e^{-kt}$$

For wastewater systems S_t is set by the legal discharge minimums, while the value of the microbial rate constant (k) is influenced by: chemistry, electron acceptor, and temperature; but can be considered constant for any particular waste stream, technology design and local climate. Equation 5 can be used in a variety of ways to understand the linkage between sewerage treatment costs and personal decisions.

If this simple model is calibrated using measured performance data from a technology then the calibrated parameters 'contain' important parts of the underlying complexity (albeit of extremely limited usefulness). Taking the OSET NTP[2] input standards as 200 g/m^3 BOD_5 (S_0 in Equation 5) and effluent concentration of 5 g/m^3 (S_t) and determining a single rate constant (k) using Equation 5 (this being a value that is the net effect of 6 or more site specific rate constants) by assuming this occurs in 7.2 days (t - the residence time for the test data for the Advantex system), results in a value of k = 0.51 g/m^3.day.

[2] On-Site Effluent Treatment National Testing Programme. For a summary of tests see (Gunn, November 2014).

The behaviour patterns of this simple, calibrated model can be seen by changing any of the parameters in Equation 5 and graphing the results. The effect of concentration changes, volume changes and nutrients (particularly N) are discussed below.

Time is a particularly important parameter in sewerage treatment, as holding time influences the volumes needing to be stored and storage is expensive. It follows that the effect of changing input volumes (and/or organic matter concentration) on time is also important as these have impacts on treatment cost via their linkage in Equation 5.

4.1 Concentration changes

Changes in input concentration occur if any (or part) of the waste streams are removed. Removal of organics will reduce BOD_5 concentrations (and nutrients). In contrast, using less water with the same organic load will increase concentrations.

Of particular note in Figure 2 are: 1/ if all BOD_5 were removed from the waste stream then treatment times reduce to 0. However if treatment times reduce to 0, then the container volume needed for treatment also reduces to 0. A readily apparent conclusion that has considerable relevance for individuals motivated to capture their nutrients, but also for decentralised systems as most of the cost of treatment can be met on-site by more sophisticated technologies.

2/ the logarithmic nature of the relationship between input BOD_5 and time is a useful characteristic. Below the reference BOD_5 (200 g/m^3) treatment time reduces rapidly, while above the reference point treatment time increases much less. A five-fold increase in concentration (200 to 1000 g/m^3) only increases treatment time by 43% (7.2 to 10.3 days).

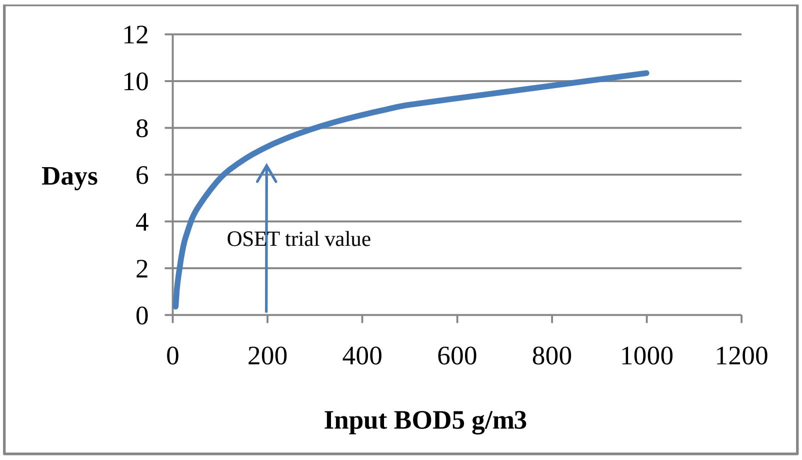

Figure 2 – Effect on holding time of changing input BOD_5 using the simple model calibrated to measured performance data of the OSET trial .

Indeed, raw faeces with an estimated BOD_5 of 96,000 g/m^3 (discussed in the Appendix) only take 19 days to reach this target.

Despite the simple model being used well beyond its derivational limits, having been calibrated using a single rate constant for a water mix of three different wastes (grey water, faeces and urine) over a seven day time period and extended to a non-water based substrate with only one of the 3 wastes (composting faeces), the experimental data is not inconsistent with the predictions (Figure 3). The biggest variation occurring later in the time period, in part because faeces will contain a higher proportion of non-digestible organic fraction and these will require a different rate constant; but also as the calibration data included sedimentation and filtration processes etc.

Hamelers (2001, p. 181) contains a data set (measuring oxygen uptake rate) using composted chicken faeces. His 2mm particle size shows a cleaner signal over the 150 hour time frame of his experiment than the data in Figure 3.

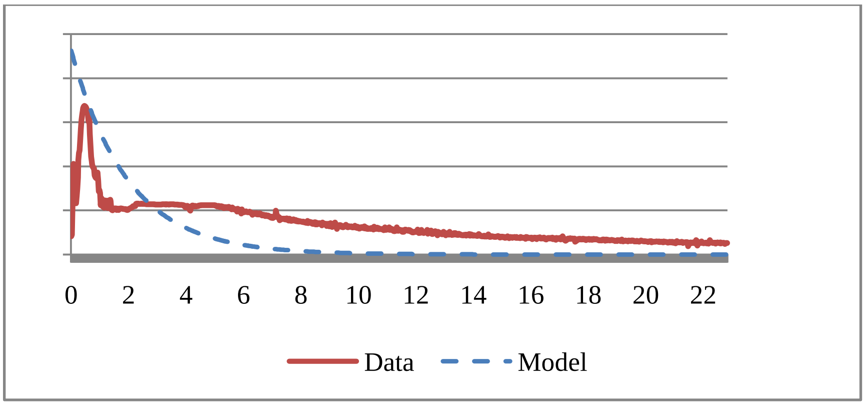

Figure 3 – Trial data from composting pig faeces at 20°C in a calorimeter. Note: 1/ non-steady state conditions occurred between peak composting and day 5 (the reactor overheated and took some time to cool) – no adjustment was made to the raw data during this period so peak composting would have been higher as energy would have gone *into* storage. This energy then needing to come *out* of storage before steady-state conditions could occur. 2/ the *Data* **y axis is W/ reactor while the** *Model* **y axis is BOD_5 m^{-3} no attempt was made to relate the two different measures to a common form except that both have a minimum of 0.**

In both sets of data, the basic model advocated here fails to identify the microbial growth phase occurring in the first few hours, and is poor beyond day 4, but reasonably captures the data sets for those crucial first few days that sewage is within our technologies. The microbial growth phase is a design issue in sewerage systems for which technologies such as activated sludge are solutions. The simple first-order kinetic model is clearly not suitable for this level of detail – but the behaviour patterns of interest here are preserved.

4.2 Reducing water volumes

Removing only water from the waste streams (such as low-flush toilets, showers instead of baths etc) means that the concentration of the organic fraction will increase (Figure 4).

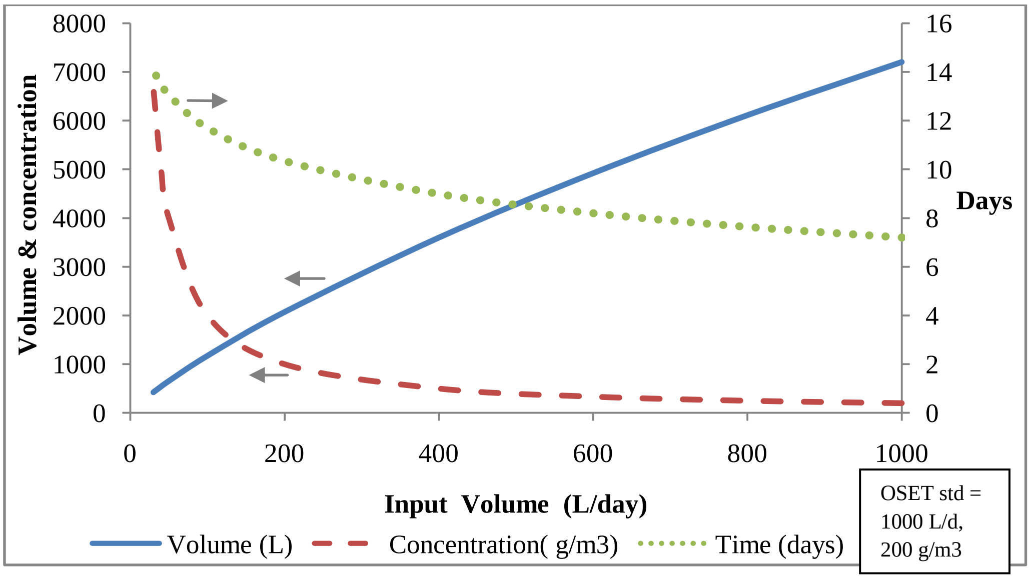

Figure 4 – The effect on container volume of using less water to carry the same organic load.

The net effect of this on the volume of the treatment container is a consequence of increased treatment times resulting from the increased concentration with reduced input volumes and can be seen in Figure 4. The reference volume is 1000 L d^{-1}, with the BOD_5 reference as above at 200 g m^{-3}.

Despite both concentration and treatment time increasing as a result of removing water from the waste stream, there is a net reduction in container volume. The per person capital cost of the treatment station can be expected to reduce; or more particularly the need for future upgrades will be delayed.

4.3 Removing Nutrients

Most nutrients are not volatile. They are found either in the sediment, taken up by the biosphere, or flushed into receiving waters. Nutrient removal is best considered using mass balance and this is discussed above (Section 3), but is also the basis of a previous paper (Chapman, 2014a).

Nitrogen in contrast to other nutrients is volatile. Along with carbon, treatment processes can release nitrogen to the atmosphere as a gas. Carbon is released as CO_2 in both aerobic and anaerobic processes; however nitrogen uses a more complex pathway using ammonia, nitrite, nitrate and nitrogen gas. Nitrification (ammonia to nitrite/nitrate) occurs in aerobic conditions, while de-nitrification (nitrate to N gas) occurs primarily in the absence of oxygen when microbes use NO_x as electron acceptor. The rate constant using NO_x is around ½ of the aerobic rate. The concentration of carbon (BOD_5) is also reduced during this process as the oxygen molecules from the NO_x need carbon to form CO_2. Nitrogen removal is one component of the waste stream for which the separate stages (septic, aerobic and anoxic) may be best separated analytically, particularly as the three stages are usually separated in space as they occur in different containers.

Nitrogen removal is a significant cost component of sewerage treatment (Smith & Katta, 2000); in effect the cost differential between a septic tank and AWS system is due to this de-nitrification process. One of these costs is the carbon feed. As carbon becomes a limiting nutrient in sewerage it is often added in liquid form. However, the major source of nitrogen is from urine, consequently if someone installs a urine separating toilet bowl and reduces their nitrogen load to the sewage then the treatment plant will be cheaper to operate. This reduced cost arises from: the reduced need for capacity for denitrification (smaller tanks); the better balance in the C:N ratio – closer to optimum (28:1) with urine removed; and reduced energy costs of oxygenating the sewage.

4.4 Reducing energy

Energy is explained by thermodynamic laws in science and in sewerage treatment is mainly needed to move mass (which includes oxygenating the sewage), with smaller energy flows from chemical energy (heat and methane production in particular). Moving mass requires energy with little differentiation between water and solids beyond the mechanisms used to move the mass - water requires pipes and pumps, in contrast to mechanical possibilities that are available for solids. Because of the linkage to mass, energy use could be based on each of the contributing components (faeces, urine and grey water) enabling comparisons between differently configured systems; which includes the processes used within a sewerage system such as: reticulation, treatment and disposal. Energy use also enables extension of system considerations to include nutrient recycling, as nutrients in a solid (and dry) form will require less energy to transport longer distances (an important consideration when the food production system is included). This consideration can be extended to the mass of carbon associated with the nutrients as well as water. Energy can also involve water supply in the analysis if technologies that use no water are included in the system.

5 Discussion

The focus for this paper arose because of the author's experience in his home town of Glenorchy. Glenorchy is a small, but growing, town of only a few hundred people currently using on-site systems but faced with the prospect of a centralised sewerage system. Because of the large capital cost of sewerage systems, all residents are required to pay. In addition, designing sewerage systems is easiest done by treating everyone as an average: a certain number of people producing a certain volume of waste with certain characteristics. This convenient engineering start point moves the focus to only the number of people and their average loads. It ignores variability within the population.

The voice of a single resident who is particularly skilled in compost toilet technologies, and would recycle all his nutrients is heard (as even the mayor is familiar with his interest), but because the system design is based on an average person he is not given the **space to be different**. Yet the effect on the cost and operation of a sewerage treatment station of an individual recycling their nutrients is deterministic and (as argued in Part II - (Chapman, 2015b)) can be accommodated. In effect this is institutional discrimination against primary adopters.

However, the role of information in moving society towards more sustainable technologies is not an engineering issue but a scientific/social one. Yet engineering is necessary to produce the improved technologies, so the issue is less about engineering and more about the space in which engineering operates. Rather than begin with a mix of the 3 waste streams, the focus should be on the environmental impacts needing to be resolved. In Glenorchy's case it is nutrients entering the lake; for which any technology that enables nutrient recycling should be in the mix of possible solutions. The analysis begins with a mass balance calculation that traces the nutrient's path through the great planetary cycles and the mechanisms by which their path can be altered by technologies to avoid environmental consequences. One of the technologies to be considered is a centralised water-based system – but it needs to compete with all the others before it can claim to be the best.

There is however, other interesting information in this series of events and that is, if this author did not reside in a town faced with a centralised sewerage system, would this paper have been written? There is enough complexity in the interface between compost toilet technologies and commerce to keep me occupied for the rest of my life – the trigger for this paper was the prospect of the sewerage system. Yet the insights contained here (and Part II) are a useful component of the whole system. So is there also a wider optimisation issue here? A need to identify *constraints in the information flow* that limit technology development for society as a whole?

In this respect, in order to cope with the complexity of the world, humans usually begin with an implicit (or explicit) set of assumptions. These assumptions are convenient as they take only a small part of the full complexity and in doing so make the problem manageable. But making these assumptions is itself a human process based strongly on the current state of knowledge. Indeed, social organisational forms such as disciplines, professions, industry, commerce etc. exist as semi-autonomous entities with behaviour patterns set by the organisational form. They only capture a part of the full complexity. In the case of sewerage, the lengthy history of the industry's evolution includes over a hundred years of use of a water-based system for dealing with our wastes. However, operating semi-autonomously allows for a behaviour pattern to evolve that becomes self referential; as the behaviour pattern gets replicated under the perceived authority of 'best practice'. While best practice has considerable functional value (engineers 'know' how to design and build sewerage systems), my experience in Glenorchy shows that it fails to respond when challenged with allowing demonstrably superior technologies to exist within the centralised system.

A set of tools by which the efficacy of our organisational forms can be judged would enable us to break out of this self referential cycle. Industry optimisation within the context of human sustainability on this planet requires that the question of the most sustainable technology is always present, creating a tension between where we are and where we could be. A theoretical perspective on the derivation and use of such a tool (called the Beacon) is contained in Chapman (2015c). This tension can then be resolved as far as possible within the socio-economic constraints of each community. This is, in effect, moving down a technology development path. Relying on a sequence of chance events for these investigations is inadequate when sustainability issues are clamouring to be heard.

6 Conclusion

Primary adopters arise from the social domain. They are a small component of the natural variability of human populations and occur in all walks of life. The primary adopters of interest in this paper are those that have an environmental conscience and the capacity to adopt different technologies to the general population. They have a low frequency of occurrence so are likely to be outvoted in a community decision based on a majority vote.

This paper looks at whether these individuals can be a useful change mechanism for an industry that is having difficulty moving towards sustainability. This is answered in the affirmative when it is shown that capturing nutrients at source (where the primary adopters can make different decisions to the general population) can result in a better environmental performance than a conventional treatment station. This potential arises from the ‘path’ that these individuals set for the spread of better technologies into society. Moving towards sustainability is partly technological and partly social. Primary adopters have strong links to social change as they live within the communities that they influence. They can be a useful component of the journey to sustainability but only if their difference is allowed to express.

Enabling a primary adopter’s difference to express from within a conventional sewerage system is argued to be possible by use of a simple first-order microbial kinetic. Using such a kinetic simplifies the spatial and temporal complexity that exists within the system but preserves the ‘patterns’ of behaviour of the system. It was further argued that calibrating this simple model with performance data from an **actual** technology embedded some of the spatial complexity of the technology into the ‘combined’ rate constant. A less than precise procedure that would not be useful for design of sewerage systems, but that enabled the patterns of behaviour arising from changes in individual behaviour to become visible, as the interconnections between the microbial world and the technology were preserved. It is these interconnections that contain the information about system behaviour that is useful in the social context as a *value* can be placed on the variation in individual contributions to the mix that we call sewage.

In establishing linkages between Nature (as she occurs within the treatment processes) and human behaviour patterns, it becomes possible to consider a range of mechanisms to enable the adoption of more sustainable technologies:

- Firstly, quantifying the significance of an individual choosing to change to more sustainable technologies opens up the possibility of using a range of fiscal tools (carrots and sticks) to enable movement towards nutrient recycling technologies by encouraging primary adopters – discussed further in Chapman (2015b). In the context of a previous paper by this author (Chapman, 2014b) an *information conduit* is established between the fundamental laws and processes (and microbial kinetics) and the economic system. That the human mind is structured to learn by trial and error and reward and punishment, means that such tools are likely to be effective in changing society towards more sustainable practices.

- Secondly, additional information signals that can be used by the commerce sector are generated by this comparatively small change in the way in which individual variability is handled in institutional decision making. In particular, the possible sale of technologies is a powerful incentive for commerce to investigate and produce technologies that are more sustainable.

All the interconnections between Nature and human use of Nature can exert their respective influence in the human social system in an appropriate manner. In effect, the information content of an economic exchange can be expanded to include Nature and human's interaction with Nature.

Nature can have a seat in the board room.

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8 Appendix

This author is not aware of any measurement of the BOD_5 of faeces. Indirect methods are used here to determine the order of magnitude of its value and the consequences on degradation times.

Lindstrom (1992) quoted a Swedish study of an apartment block that separated blackwater and greywater. 44% of the BOD_5 was in the blackwater and measured at 20 g P^{-1} d^{-1}, but note that this measurement includes urine and faeces. Feachem (1983, pp. 7 - Table 1-3) estimated faeces BOD_5 at 96 mg g(wet)$^{-1}$ (14.4 g(BOD) d^{-1} @ 150 g(wet) d^{-1}) – while urine is estimated at 10.3 g(BOD) d^{-1} @ 1.2 L d^{-1}). A different perspective can be got from Lentner (1981, p. 152) who noted the energy content of faeces at 0.58 MJ d^{-1} which, if composed of glucose and fully degradable in 5 days, then BOD_5 could be determined by stoichiometric analysis (1 KJ heat consumes 0.06659 g O_2) giving a BOD_5 estimate of 38 g P^{-1} d^{-1}.

Taking the Lentner data of 38 g P^{-1} d^{-1} and a faecal volume of 0.150 L d^{-1} would give a BOD_5 estimate of 253000 g m^{-3}. This is likely to be an overestimate as some of the organics in faeces (lignin) will be difficult to degrade by bacteria in 5 days and hence would not be measured in a BOD_5 test. Indeed the 96000 g m^{-3} of Feachem is 38% of the Lentner data and this value is consistent with faeces containing a high proportion of poorly degradable substrates.

Using the BOD_5 estimate of Feachem of 96000 g m^{-3} in Equation 5 the time for faeces degradation to discharge levels is 19 days. The total volume needed for this is 0.150*19 = 2.8 Litres; such is the nature of logarithmic changes interacting with conservation of mass laws.