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The 16th Environmental Researchers’ Colloquium was hosted by University College Dublin in January 2006. This annual meeting is organised jointly by the host institution and by the Environmental Sciences Association of Ireland (ESAI). It aims to provide postgraduate researchers with a supportive forum in which to present papers and learn about research being undertaken in other third level institutions both in Ireland and elsewhere.

Standards have always been high, but increasing levels of funding for environmental research has meant that both the research and the resultant papers have tended to increase over time in quality and interest.

At the 2006 ESAI Annual General Meeting, the decision was taken to publish papers in Proceedings, and an invitation was extended to all paper and poster authors to submit short papers for review. Subsequently, all papers received were peer-reviewed and went through an editing process, as would be required by an academic journal. In this way, young researchers gained practical experience in publishing their work, and ESAI was able to create a permanent record of research in progress or completed by some Irish postgraduates.

Much hard work has gone into the production of these Proceedings, and many already busy people volunteered to take on tasks to ensure that a high standard of presentation was achieved. Special thanks are due to the paper authors, ESAI Council members and chairperson, and to Cóilín MacLochlainn for his careful and thorough work in preparing manuscripts for the printers. ESAI provided funds to cover formatting and publication costs.

It is the intention of ESAI to publish proceedings of the 2007 and subsequent Environmental Researchers’ Colloquia, and all researchers are encouraged to take advantage of this opportunity to provide postgraduates with useful experience in getting their work published.

Professor Richard Moles,
Editor
CULTIVATING THE UNCULTURABLE? THE ROLE OF CRENARCHAEOTA IN ANAEROBIC WASTEWATER TREATMENT SYSTEMS

Carol Morris, Thérèse Mahony, Rory McKeown, Joseph O’Reilly, Dirk DeBeer, Armin Gieseke, Gavin Collins and Vincent O’Flaherty

ABSTRACT

The three-domain classification divides life into three major groupings: Bacteria, Archaea and Eucarya (Woese et al., 1990). The Crenarchaeota are a kingdom within the Archaea and its members are primarily defined by rRNA gene sequence similarity. Initially, it was believed that Crenarchaeota were associated only with extreme environments and represented archaic life forms adapted to the harsh environmental conditions that existed on Earth billions of years ago. Recently, however, and by applying cultivation-independent molecular tools, it has become evident that Crenarchaeota are ubiquitous and highly abundant in many non-extreme environments, including soils, lakes and oceans. Until recently, despite the efforts undertaken to describe and characterise the occurrence of Crenarchaeota in various environments, cultivation of isolates or consortia containing non-thermophilic Crenarchaeota has proven very difficult. Here, we review novel strategies undertaken to isolate consortia containing non-thermophilic Crenarchaeota and to elucidate their in situ functionalism in non-thermophilic environments. Furthermore, we review reports of large populations of Crenarchaeota in granular biofilms of anaerobic wastewater treatment systems and preliminary work focused on the explication of their in situ physiological roles. Further advances in this regard will have significant implications for the understanding of key microbe-driven nutrient cycles and for the development of new environmental technologies.

Key words: anaerobic digestion; Crenarchaeota; ecophysiology; microbial diversity; wastewater

INTRODUCTION

Since the time of Darwin efforts have been made to generate a natural classification system dividing all life forms in the biosphere into groups or kingdoms that reflect characteristic similarities or differences. Darwin himself believed that life could be divided into two kingdoms: the Animalia (animals) and the Plantae (plants). This elementary divisionary system was functional. However, following the work of later, pioneering ecologists such as Hackle (1886), Copeland (1938) and Whittaker (1959), the Protista (uni- and multi-cellular organisms), the Monera (simple bacteria) and the Fungi were added respectively. The then five-kingdom system, comprising the Animalia, Plantae, Protista, Monera and Fungi, offered a clear and concise outline of the division of life.

The five-kingdom system was based primarily on clearly identifiable physiological characteristics shared between organisms, such as shape, size, colour, texture, etc. However, this strategy was also rendered redundant as the diversity of organisms in the biosphere began to unfold. The abundance and diversity of microorganisms, in particular, forced a reformulation of divisionary criteria. Specifically, combined scientific efforts in the 1960s, focused on the scrutiny of various cellular components, led to the generation of a classification system consisting of two separate kingdoms: the Prokaryotes and the Eukaryotes. Prokaryotic cells are less complex than eukaryotic cells at several levels, which are structurally and biochemically more complex, e.g. eukaryotic cells have a higher degree of organisation than prokaryotic cells in that they contain many organelles or structures separated from the other cytoplasm components by a membrane, whereas prokaryotic cells contain no organelles (Prescott et al., 2002).

However, and in a more recent context, Woese et al. (1990) rejected previous classification systems and, instead, shifted the basis for the definition of organisms from the cellular to the molecular level. In vivo digestion of labelled 16S rRNA using T1 ribonucleases allowed them to accumulate catalogues of oligonucleotide sequences, which were then employed in comparative analysis studies that resulted in the generation of dendograms illustrating the relatedness of organisms. This work highlighted a deep split within the prokaryotes. Unique clusterings of methanogenic bacteria were discovered by using these molecular classification methods and, thus, propelled Woese and Fox to propose that these organisms and closely related species be termed Archaeabacteria, which considered their close relatedness with eubacterial (‘true bacteria’) species but also their archaic origins (Woese & Fox, 1977; Jurgens, 2002). The well-studied rRNAs provided a distinguishable feature shared between the three groups, allowing for the generation of a natural classification system. The tripartite tree of life proposed by Woese et al. (1990) divides all forms of life into three distinct groups: the Bacteria (formally Eubacteria), the Archaea (formally Archaeabacteria) and the Eucarya (formally Eukaryotes).

Up to this point, phylogenetic distinction was reliant on traditional culture-based techniques. However, the limitations of culture-based, molecular techniques became apparent and, indeed, were and are well documented (e.g. Staley & Konopka, 1985). Specifically, it is thought that more than 90% of extant microbial species have avoided detection by traditional selective cultivation techniques, especially where these techniques are employed as independent approaches (Ward et al., 1992). Instead, and by employing cultivation-independent molecular tools that
incorporate genetic markers, such as the small subunit (SSU) rRNA, some of the limitations of selective enrichment cultivation techniques can be alleviated. The use of biomolecular strategies to study microbial ecology is most acutely apparent in the case of the *Archaea*.

The *Archaea* were originally divided into two phylogenetically distinct groups, the *Crenarchaeota* and the *Euryarchaeota*. By employing traditional culture-based molecular methods, the *Euryarchaeota* are identified as haplophilic, methanogenic organisms living under extreme thermophilic conditions, while the *Crenarchaeota* are described as hyperthermophilic, obligate anaerobes with sulphur-dependent metabolisms. However, the introduction of cultivation-independent molecular tools has led to the realisation that the *Archaea* are much more cosmopolitan than originally thought; in fact, through the application of these techniques a third lineage within the *Crenarchaeota*, called the *Korarchaeota*, has been identified (Barnes et al., 1996). Archaeal sequences have been retrieved from various non-thermophilic environments, including agricultural and forest soils (Bintrim et al., 1997; Jurgens et al., 1999; Sandaa et al., 1999; Simon et al., 2000; Ochsenreiter et al., 2003), oceanic plankton (DeLong, 1992; Furuhrman et al., 1992), sediments (MacGregor et al., 1997; Schelpe et al., 1997; Jurgens et al., 2000; Keough et al., 2003) and in the deep subsurface (Taki et al., 2001). The detection of these organisms would not have been possible in the absence of cultivation-independent techniques. Moreover, the abundance of these 'unculturable' *Archaea* prompts the presumption that the full extent of archaeal diversity will continue to emerge as the sophistication of molecular ecology techniques evolves.

The Kingdom *Crenarchaeota* is of particular interest, primarily due to the ability and, often, preference of cultivated members to grow at extremes of temperature and acidity. For example, members of the crenarchaeal order Sulfolobales flourish at pH 1-2 and die above pH 7. Members of the group *Pyroboius* have exhibited a maximum growth temperature of 113°C. Most species are unable to grow at temperatures below 70°C but can maintain vitality at low temperatures for long periods (Barns & Burggraf, 1997) The robustness of their cellular enzymes, which are capable of withstanding the conditions prevailing in such extreme environments, has attracted interest from biotechnology sectors seeking to exploit the capabilities of these microorganisms. The *Crenarchaeota* have also attracted the attention of evolutionary biologists and exobiologists striving to study microbial evolution.

Recent years have seen the unearthing of an abundance of crenarchaeal sequences from several non-thermophilic marine and terrestrial environments. These temperate environments include: forest and subsurface soils reported from the United States, Japan and Finland (Bintrim, 1997; Jurgens & Saano, 1999; DeLong, 2003); marine picoplankton (DeLong, 2003); the gut of a deep-sea holothurian (McInerney et al., 1995) and marine sponges (Preston et al., 1996). Crenarchaeal rRNA gene sequences have also been detected in anaerobic granular biofilms, sampled from bioreactors operating at mesophilic temperatures (Collins et al., 2003; Collins et al., 2004; McHugh et al., 2004). These authors also highlight the abundance of these non-thermophilic *Crenarchaeota* in the environments studied. For example, Collins et al. (2005a) report crenarchaeal abundance constituting 25-35% of total archaeal populations within the methanogenic biofilms studied.

Six phylogenetically distinct groups of the non-thermophilic *Crenarchaeota* have been generated, as outlined by Ochsenreiter et al. (2003): 1.1a – marine freshwater and subsurface; 1.1b – soil freshwater and subsurface; 1.1c – forest soil and freshwater; 1.2 – marine/freshwater sediments; 1.3a – marine, hotspring and freshwater; 1.3b – freshwater, wastewater and soil. Although the presence and abundance of these non-thermophilic *Crenarchaeota* have been documented, the absence of cultured isolates has hindered an explication of their role in the biosphere. Their *in situ* functionalism and ecophysiology remain unknown and only speculative hypotheses regarding their geochemical roles have been proposed (e.g. Collins et al., 2005a). The surprising abundance and ubiquitous nature of these
novel crenarchaeal organisms, however, imply that they may play a role in the biogeochemical cycles governing the biosphere. Efforts are now focused on the elucidation of the role of the Crenarchaeota.

**CRENARCHAEOTA IN NON-THERMOPHILIC ENVIRONMENTS**

Elucidation of the ecophysiological role played by the Crenarchaeota in the biosphere is the underlying aim of the study of these microorganisms. The presence and abundance of the Crenarchaeota in various habitats are well-documented, and now innovative studies are beginning to suggest possible roles of the microorganisms. Simon et al. (2005) adopted cultivation and molecular phylogenetic techniques including PCR-single-strand-confirmation polymorphism (SSCP), fluorescent in situ hybridisation (FISH) and real-time PCR, and suggested that one of the two dominant phylotypes of Crenarchaeota colonising tomato plant roots grown in soil could be selectively enriched in mixed cultures amended with root extract. The clones retrieved from the root extract-enriched cultures were phylogenetically grouped with sequences from group 1.1b, as outlined by Ochsenreiter et al. (2003). This work further extended previous studies carried out, which indicated that the rhizosphere is influential over the crenarchaeal soil assemblage and that an association is apparent between mesophilic soil Crenarchaeota and plant roots. Moreover, the study provides early evidence of successful culturing techniques for non-thermophilic Crenarchaeota. Furthermore, these findings are consistent with studies carried out by other research groups also detailing the recovery of SSU rRNA gene sequences of mesophilic Crenarchaeota from the rhizosphere, e.g. rice rhizosphere (Grobkopf et al., 1998), the roots of washed maize (Chelius & Triplett, 2001) and mycorrhizospheres of pine seedlings (Bomberg et al., 2003).

The modest increase (10^2) in SSU rRNA gene copy number observed by Simon et al. (2005) over total incubation time correlates with results from other studies that have also attempted to enrich and isolate Archaea and Bacteria identified only through molecular phylogeny. Examples include bacterial isolates of Acidobacteria, Verrucomicrobia, Gemmatimonadetes, Actinobacteria and Proteobacteria obtained after extended incubations and enrichments of anaerobic methane-oxidising Archaea from marine sediments (e.g. Janssen et al., 2002; Joseph et al., 2003; Stevenson et al., 2004).

The design and incorporation of a novel in situ cultivation method in combination with a more ‘conventional’ molecular ecological technique (i.e. FISH) in a recent study shows that previously unknown Crenarchaeota thrive in cold sulphidic marsh water and constitute a significant proportion of a symbiotic microbial community (Koch et al., 2006). The authors report the identification, in situ cultivation and life cycle of a microbial community consisting of a novel cold-loving crenarchaeote tentatively called ‘Cre 1,’ the bacterial genus Thiothrix and the bacterium ‘Sip100.’ Interestingly, ‘Cre 1’ was demonstrated, by extended fluorescent in situ hybridisation studies, to be at all times attached to the bacterial community member ‘Sip100.’ Furthermore, it was also observed that the ‘Cre 1’ might be incorporated in a host dependent relationship, as it was never observed in free-living form. This crenarchaeal/bacterial community provides a significant opportunity for future investigations which are hoped will lead to the identification of interesting physiological and ecophysiological insights to the close microbial relationship observed in cold sulphidic environments. These insightful studies are representative of much work

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**Figure 2. Example of phylogeny of crenarchaeal small-subunit rRNA genes based on the Kimura-two parameter algorithm from Collins et al. (2005).** Bootstrap replicates (from a total of 100 replicate samplings) that supported the branching order are shown at relevant nodes. Scale, 1 nucleotide substitution per 100 sequence positions. GenBank accession numbers of crenarchaeal clones from this study are presented in bold, with the source biomass shown in parentheses.
aimed at the elucidation of the \textit{in situ} functionalism of the \textit{Crenarchaeota} in non-thermophilic environments.

The presence and abundance of non-thermophilic \textit{Crenarchaeota} in anaerobic wastewater treatment systems is well reported (e.g. Godon \textit{et al.}, 1997(a); Godon \textit{et al.}, 1997(b); Leclerc \textit{et al.}, 2004). This finding, however unexpected, now has significant implications for our understanding of the role of the \textit{Crenarchaeota} within the biosphere. Anaerobic bioreactors appear to provide an ideal opportunity to study these cosmopolitan organisms due to their ability to cultivate anaerobic consortia containing large populations of non-thermophilic \textit{Crenarchaeota}. In essence, the anaerobic bioreactors provide a model habitat for studying these organisms.

\textbf{CRENARCHAEOTA IN ANAEROBIC WASTEWATER TREATMENT SYSTEMS}

Anaerobic wastewater treatment systems (AWTS) have been in development for more than a century. The past few decades have seen a surge in levels of research into this technology, primarily focused on the application of efficient AWTS to a broader range of wastewaters. Increased understanding of the microbial process driving the technology and the development of innovative bioreactor designs, e.g. the upflow anaerobic sludge bed (UASB) reactor (Lettinga & Hulshoff, 1991), anaerobic filter and expanded granular sludge bed (EGSB) reactor (Kato \textit{et al.}, 1994) has improved this technology, which is now widely used for the remediation of various wastewaters.

The microbial communities, and granular biofilms, formed within the anaerobic reactors are responsible for the sequential microbial process termed anaerobic digestion (AD), whereby the microbial populations are involved in the biological mineralisation of organic compounds to methane and carbon dioxide (Zeikus, 1982). AD is a virtually ubiquitous, natural process occurring in oxygen-depleted, moisture-rich environments, such as paddy-fields and river sediments. Anaerobic reactors are often operated as ‘black boxes’ with material balances, such as methane content and effluent quality, used to monitor most full-scale treatment processes. However, this approach is insufficient to allow optimal process design and performance as the capacity of the microbial biomass in the reactor, and its response to environmental conditions are not addressed (McHugh \textit{et al.}, 2003). Improved characterisation of the microbial communities underpinning the AD process has the potential to enhance the operational stability, efficiency and applicability of the AD approach.

Culture-independent techniques used in the study of complex microbial communities have greatly increased our understanding of the microorganisms present in anaerobic granular biofilms (Hunter-Cevera \textit{et al.}, 1998). The use of techniques such as 16S rRNA gene clone

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure3.png}
\caption{TRFLP electropherograms illustrating crenarchaeal dynamics (TRF, 235 bp) in (A) R1 and (B) R2 on the following days during the trial period: (i) 0 [hydraulic retention time (HRT), 24 h], (ii) 21, (iii) 71 [after HRT reduction to 12 h], (iv) 218 [after HRT reduction 8 h], (v) 309, (vi) 354, (vii) 409 and (viii) 500.}
\end{figure}
library analyses allows for the generation of complete microbial inventories from complex microbial communities, e.g. anaerobic granular sludge (Godon et al., 1997a; Dojak et al., 1998; McHugh et al., 2003). In addition, nucleic acid fingerprinting techniques can provide patterns or profiles of microbial diversity within the community, and can be applied to achieve high-throughput analysis of temporal microbial community dynamics in functioning bioreactors.

Collins et al. (2005a) investigated the distribution, localisation and phylogeny of abundant populations of Crenarchaeota in anaerobic granular sludge samples from eight full- and laboratory-scale anaerobic bioreactors (S1-S8). The microbial community structure of the granular sludge samples was determined using 16S rRNA clone library analysis, and crenarchaeal distribution within the granules, along with substrate uptake patterns of the granular biofilms, were investigated using FISH and beta microimaging (Gieseke et al., 2005) respectively. In addition, temporal crenarchaeal dynamics, in response to process stimuli, within two laboratory-scale bioreactors (R1 and R2), were determined by TRFLP analysis (Collins et al., 2005c). The availability of a laboratory-scale model system, capable of sustainable cultivation of the non-thermophilic Crenarchaeota, allowed application of microbial ecological techniques to assess the role of these organisms in AD, and the interactions between the members of the methanogenic consortium.

Community structure analyses by Collins et al. (2005a) revealed the absence of crenarchaeal clones in three of the eight bioreactors sampled. However, the five remaining bioreactors revealed high abundances of uncultured Crenarchaeota: S1-69%, S5-55%, S6-59%, S7-14% and S8-78% of all archaeal clones, respectively. The crenarchaeal clones recovered from these anaerobic sludge samples appear to hold a well-defined phylogenetic coherence, as all clones belong to Group 1.3 of the Crenarchaeota (DeLong 1998; Jurgens & Sano, 1999), or 1.3b as proposed by Ochsenreiter et al. (2003; e.g. Fig. 2).

The archaeal 16S rRNA genes from the bioreactors studied by Collins et al. (2005c), which were applied to the treatment of a whey-based wastewater, and were operated at temperatures ranging from 12°C to 18°C, were analysed by TRFLP, and indicated that the relative abundance of specific terminal restriction fragments (TRFs) underwent changes, which correlated with process-related activities (Fig. 3). Crenarchaeota-, Thermophilus- and Sulfolobus-like TRFs were present throughout the reactor trial period. The crenarchaeal TRFs were detected in abundance at the end of the trial period in R2; however, R1 demonstrated a direct correlation between crenarchaeal dynamics and operational perturbations applied to the bioreactor. The responsive dynamics of the Crenarchaeota-like TRFs in R1 indicates that the organisms fulfil an important role in the anaerobic digestion process. Furthermore, the presence of Crenarchaeota-like organisms in R1 and R2 coincided with efficient reactor performance and with an abundance of acetoclastic methanogens.

The study of Collins et al. (2005a) revealed an overestimation of Crenarchaeota-like species determined by clone library analysis, whereby FISH analysis allowed, instead, for determination of the abundance of Crenarchaeota as a fraction of the total area of granule cross sections (n=20) used. Thus, the authors concluded that a polyphasic approach was important for the compilation and analysis of ecological inventories. By FISH, the Crenarchaeota comprised 50% of all Archaea and 15-25% of the total sludge microbial consortia. The crenarchaeal cells were rods of 1.5 µm long and 0.7 µm wide, which appeared in dense cluster formations within the architecture of the granule (Fig. 4). Interestingly, crenarchaeal cells were observed in juxtaposition with acetoclastic Methanosaeta cells toward the periphery of specimen sections (granule surface).

A radioactive tracer technique (Andreasen & Nielsen, 1997) in conjunction with beta imaging allowed the authors to investigate substrate uptake patterns of the granular biofilms in the S1 bioreactor. Radiotracer incubations were carried out on granular biofilm samples taken from S1, which were then cross-sectioned and scanned for radioactivity. The data suggested an accumulation of radioactivity in the outer layer of the S1 sections (Fig. 5). Localisation of radioactivity in this area of the granule coincided with FISH observations of juxtaposed Crenarchaeota and Methanosaeta cells at the surface of the granule. Thus, the authors postulated that the Crenarchaeota are active members of the microbial consortia in the granular biofilms and, furthermore, that a metabolic interaction existed between the Crenarchaeota and acetate-utilising methanogens. The authors could draw the following conclusions: (i) Crenarchaeota belonging to group 1.3 are prevalent and highly abundant in granular biofilms and, furthermore, the Crenarchaeota can be cultivated in laboratory-scale bioreactors as members of the methanogenic microbial consortia; (ii) a definite crenarchaeal structure was illustrated within the architecture of the granules using FISH; (iii) the use of more specific oligonucleotides primer sets for TRFLP analysis will allow greater insight to dynamics within crenarchaeal communities; (iv) low temperature anaerobic bioreactors provide a model habitat for the cultivation of Crenarchaeota as part of the microbial consortia within the bioreactors.

The importance of the Crenarchaeota within anaerobic granular sludge...
Ecophysiology of non-thermophilic Crenarchaeota

The full in situ ecophysiology of the Crenarchaeota will (a) benefit our understanding of microbial interactions and the ecology of Crenarchaeota in the biosphere and (b) improve the efficacy of biotechnological applications, such as waste treatment systems.

FUTURE PERSPECTIVES

The literature outlined in this paper forms the basis for a number of theories regarding the role played by Crenarchaeota in various non-thermophilic environments and, in particular, suggests a number of symbiotic and/or host-dependent interactions between non-thermophilic Crenarchaeota and other organisms in aquatic, terrestrial and engineered habitats. In the case of the AD process, the proximity of the Crenarchaeota to methanogenic populations in granular biofilms suggests that the Crenarchaeota may be active in supplying substrates for utilisation by methanogens, e.g. acetate. Furthermore, occurrences of the Crenarchaeota on the surface of the granules and along deep channels extending through the granules, suggest that the Crenarchaeota may be prominent in the initial breakdown of wastewater constituents. Future work in this area should focus on testing these hypotheses. Anaerobic reactors provide a highly efficient means of cultivating Crenarchaeota-containing biofilm consortia – and therefore a useful model system for the study of these organisms. To this end, the full in situ ecophysiology of apparently important Crenarchaeota in anaerobic granular biofilm should now be elucidated to: (a) enhance our understanding of microbial interactions and ecology in terrestrial and aquatic habitats and (b) improve the efficacy of biotechnological applications such as waste treatment systems.

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REFERENCES


Haeckel, E. 1866. Generelle morphologie der Organismen. George Reimer,
DEVELOPMENT OF METABOLISM ACCOUNTING METHODS FOR SUSTAINABILITY APPRAISAL OF 79 IRISH SETTLEMENTS

Walter Foley, John Morrissey, Richard Moles and Bernadette O’Regan

ABSTRACT

An Environmental Protection Agency (EPA) funded ERTDI (Environmental Research Technological Development and Innovation) study of 79 settlements commenced on 1st March 2002. It was proposed in part to achieve metabolism accounting of material flow networks within and between settlements. Metabolism accounting is a systematic assessment of the flows and stocks of material within a system defined in space and time. The metabolism of most ‘modern’ settlements is essentially linear, with resources flowing through the urban system. It seems unlikely that the planet can continue to accommodate an urbanised humanity, which routinely draws its resources from a distant hinterland. The basis for this research on material and energy flow is that it can help develop a circular pattern of urban metabolism vital to sustainable development. For the development of material, energy and waste oriented policies, knowledge about the flow, use and disposal of materials through society is necessary. Data were collected for selected settlements from a 79-settlement sample. Identification of data required and data available, and the means of gaining information both necessary and valuable but currently not available, were fundamental tasks of this research. Ecological Footprints (EFs) were then calculated depending on the degree of privileged information for specific settlements. The research has helped identify critical parameters in settlement sustainability in Ireland, with special attention to the importance of size, functionality, geographic location and place in the spatial hierarchy. The research will allow the development of effective, practical recommendations regarding the integration of sustainability goals into Irish settlement planning.

INTRODUCTION

The purpose of this paper is to demonstrate variations in different metabolic flows in a range of Irish settlements and indicate the various policy implications associated with these variations. At domestic scale, transport flows, home energy requirements, waste production, food consumption and water consumption were selected for investigation. Energy and water consumption were chosen here as representative samples of the work required and results obtained. The collated data for each sector were transformed into an Ecological Footprint (EF) for evaluation of 79 Irish settlements (Fig. 1). Where possible, CO₂ equivalent emissions were calculated to facilitate ease of conversion to EF values. These initial results and EFs are presented for each metabolic flow across the 79 settlements. The results were examined according to the settlement parameters of size, functionality, geographic location and position within the spatial hierarchy of settlements.

The EF is essentially a representation of material flow indicators which assess human demand against natural available capital (Wackernagel et al., 2004). EF does not attempt to measure the social or economic dimensions of sustainability but contributes to the environmental or ecological aspect of sustainability measurement within society (van Vuuren & Bouwman, 2005). The EF serves as a practical tool to enable planners and policy makers to identify areas where reductions of their region’s ecological demand are most feasible (Barrett & Scott, 2001). One criticism of the EF is the non-standard nature of methodologies (Leighton, 2004).

Within the work reported here, EF was adopted as a comparative metric for the sustainability of the 79 settlements. It does not represent an exact measurement of the EF (at household level) of a settlement, as not all material and energy flows were included in the study and a complete EF was not executed for all flows under study.

Therefore, the EF within the context of this research provided:

1) a means of comparing the environmental demand of settlements;
2) a means of identifying those settlements which were most environmentally sustainable;
3) a means of comparing the dynamic flows of settlements. The EFs did not address the built environment but rather the interactions within the built environment;
4) a metric for inter-settlement comparisons of components of EFs, such as energy, transport, solid waste and water.

The EF did not:

1) provide a means to identify those flows which caused the greatest impact within a settlement, as not all flow analyses were complete. It is acknowledged that EFs offer a conservative estimation of environmental impact (Loh & Wackernagel, 2004);
2) represent a dynamic measurement of settlement sustainability, but rather a fixed appraisal of settlement sustainability with data concentrated around the year 2003.

The research was part of a larger study titled Sustainability and Future Settlement Patterns in Ireland (SFSPI). Combined with metabolism accounting, sustainability indices allowed ranking of settlements and the development of a Sustainable Development Index. The overall results of the analyses will provide input into
Ireland’s National Spatial Strategy. In addition to contributing to spatial development policy, the research will provide benchmarks for strategic environmental assessment and integrated socio-economic-environmental assessment of urban growth. Major gaps in available information were found to exist in relation to flows at settlement scale, and these were filled through questionnaire surveys undertaken in each of the 79 settlements. Moreover, these survey data were also aggregated, when necessary, during the development of flow methodologies.

For example, the 79 settlements were categorised into seven Classes. This aggregation of settlements increased sample size for data analysis without compromising the integrity of the data, allowing for a more robust dataset for comparisons and the identification of sustainability patterns. Data selected on which the classification was based shared the following characteristics: they were available for a wide range of the settlements; they reflected the differences and similarities of settlements across a spectrum of socio-economic and environmental issues; they were reliably accurate; and they related to attributes which showed variations amongst settlements. Some attributes on which the classification was based were: average monthly income; distance to settlement of equal or greater size; tertiary service level; population size. The settlements were categorised through a series of iterative stages of correlations, detecting most significant relationships.

Additionally, a Services Index was developed as a measure of settlement tertiary service level. Forty services were included in the calculation of this Services Index for all 79 settlements. Services in the index included: shops, hospitals, banks, public transport stations. For example, local primary schools were given a score of 1, as they were generally present in every settlement including lower-order smaller settlements. Local Police Stations and Post Offices were given a score of 2, as they occurred less frequently in settlements. Finally, services of a high order with an infrequent occurrence – for example, hospitals – were given a score of 3. The precise definitions for a lower-order service, such as a small shop, or a higher-order service, such as a hospital, were to some extent subjective, but were based on detailed

| Table 1. Change in overall consumption of energy 1990-2003 (SEI, 2005). |
|---------------------------------|------|-------|-------|
|       | % Consumption | % 1990 Share | % 2003 Share |
| Oil   | +195          | 16          | 37      |
| Coal  | -52           | 27          | 10      |
| Natural Gas | +360 | 5      | 19      |
| Peat Turf | -69       | 26          | 6       |
| Peat Briquettes | -40 | 7      | 3       |
| Electricity | +68      | 16          | 22      |
data collection and examination. A key assumption is that settlements with higher-order services will generally possess the services provided by settlements with lower-order services (Grove & Huszar, 1964).

**HOUSEHOLD ENERGY**

This section is concerned with residential energy use and resultant CO2 emissions and is chosen as a representative example for all component flows. Over the period 1990-2001 Ireland’s total annual energy consumption grew in absolute terms by 57%. Though the use of natural gas increased by 117% during the period 1990-2001 (7% per annum), the supply of natural gas to SFSPPI settlements remained largely unchanged (CSO, 1991, SAPS; CSO, 2002a).

With regard to energy demand of final consumers, oil consumption, natural gas consumption and electricity usage all rose, whereas solid fuel consumption declined. By 2003, oil and gas were steadily replacing solid fuels as residential fuel choice (Table 1). Household energy consumption increased overall by 23% in the period 1990 to 2003; however, its share of total final consumption decreased from 30% to 24%. The increase in energy use in the transport sector was largely responsible for this change (SEI, 2003). The change in total fuel consumption is shown for 1990 and 2001 in Figure 2.

Electricity consumption is the single greatest contributor to the production of greenhouse gases. Rates of emission depend on the energy mix and efficiency of the generating stations (IEA, 2003; UNEP, 2000). Whereas most OECD countries have a balance of conventional sources, Ireland continues to lag behind with regard to energy production from renewable and other sources (for example, CHP, wind). The government policy aims at reaching 13% energy supply from renewable sources by 2010 (DETE, 2005).

Geographic location, the transition to a deregulated market, and climate change are principal factors affecting the efficiency and competitiveness of the Irish electricity market (DETE, 2005). Ireland suffers from a lack of domestic energy resources, and in 2000 only 15% of the state’s energy came from indigenous sources (DETE, 2005). Traditional peat-fired generators, hydroelectric stations and gas reserves off the Irish coast are not sufficient to substantially reduce dependence on imported fuels, such as oil, gas and coal (DETE, 2005), leaving Ireland vulnerable to price and supply changes. With nuclear power generation an apparent non-option, the promotion of renewable green energy is critical to the future of sustainable energy production in Ireland. Moreover, the UK, one of the largest oil and gas producers in Europe, is switching from being a gas exporter to being a gas importer (DETE, 2005). Electricity prices for industrial customers in Ireland increased for the period 2001-2004 by approximately 40% (DETE, 2005).

In relation to specific new EU states, industrial electricity prices in Ireland are 20% higher than Hungary’s, 60% higher than the Czech Republic’s, and 76% higher than Poland’s (DETE, 2005). At the end of 2004, the Commission for Energy Regulation (CER) approved two increases in domestic charges, amongst other sectors, with a cumulative effect of a 13% increase (DETE, 2005).

**METHODOLOGY**

The single most important issue with regard to residential CO2 equivalent emissions was the acquisition of appropriate emission factors (UNEP, 2000). The following conversion factors (Table 2) were available from an Irish EPA report entitled Carbon Taxes: Which Households Gain or Lose? which was prepared by the Economic and Social Research Institute (ESRI) (EPA, 2004a):

<table>
<thead>
<tr>
<th>Energy (Fuel)</th>
<th>Units</th>
<th>CO2 Emission Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas</td>
<td>kWh</td>
<td>0.197 kgCO2/kWh</td>
</tr>
<tr>
<td>Electricity</td>
<td>kWh</td>
<td>0.75 kgCO2/kg</td>
</tr>
<tr>
<td>Anthracite</td>
<td>kg</td>
<td>2.88 kgCO2/kg</td>
</tr>
<tr>
<td>Coal (bituminous)</td>
<td>kg</td>
<td>2.63 kgCO2/kg</td>
</tr>
<tr>
<td>Turf (loose)</td>
<td>cwt*</td>
<td>69.15 kgCO2/cwt</td>
</tr>
<tr>
<td>Turf (briquettes)</td>
<td>bale**</td>
<td>22.92 kgCO2/bale</td>
</tr>
<tr>
<td>Central heating oil</td>
<td>litres</td>
<td>2.65 kgCO2/litre</td>
</tr>
<tr>
<td>LPG</td>
<td>kg</td>
<td>3.01 kgCO2/kg</td>
</tr>
</tbody>
</table>

*One cwt (hundred weight) is equivalent to 50.8kg
**One bale of briquettes is approximately 12.5kg

Table 3. Results sample for CO2 emissions. (Average units per household are multiplied by the appropriate emission factors to give CO2 emissions per household.)
Table 4. A selection of settlements are provided with varying CO₂ emission results.

<table>
<thead>
<tr>
<th>Settlement</th>
<th>Population</th>
<th>Natural Gas</th>
<th>Yearly per capita kgCO₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ennis</td>
<td>22,051</td>
<td>√</td>
<td>2,201</td>
</tr>
<tr>
<td>Castleconnell</td>
<td>1,343</td>
<td>√</td>
<td>2,049</td>
</tr>
<tr>
<td>Patrickswell</td>
<td>998</td>
<td>√</td>
<td>2,203</td>
</tr>
<tr>
<td>Adare</td>
<td>1,102</td>
<td>√</td>
<td>2,078</td>
</tr>
<tr>
<td>Annacotty</td>
<td>1,342</td>
<td>√</td>
<td>1,714</td>
</tr>
<tr>
<td>Crafooe</td>
<td>656</td>
<td>√</td>
<td>2,243</td>
</tr>
<tr>
<td>Portarlington</td>
<td>4,001</td>
<td>√</td>
<td>3,087</td>
</tr>
<tr>
<td>Edenderry</td>
<td>4,559</td>
<td>X</td>
<td>3,658</td>
</tr>
<tr>
<td>Athlone</td>
<td>15,936</td>
<td>√</td>
<td>2,627</td>
</tr>
<tr>
<td>Mullingar</td>
<td>15,621</td>
<td>X</td>
<td>2,903</td>
</tr>
<tr>
<td>Sligo</td>
<td>19,735</td>
<td>X</td>
<td>2,644</td>
</tr>
</tbody>
</table>

2005). CO₂ emission factors were then applied to each fuel type for each settlement and totalled (Table 3).

Table 4 shows a sample set of settlements with corresponding CO₂ emissions, which are directly attributable to residential energy use. The majority of settlements in the table have natural gas supply.

Settlement size does not have a major effect on residential energy emissions of CO₂. Geographical location, however, is a factor in CO₂ emissions. This is evidenced by comparison of Athlone and Ennis, for example, which are both relatively large settlements, yet whose per-capita emissions differ by over 400kg CO₂ per capita per annum. Moreover, there is the factor that certain counties are known as “coal counties” – that is, port locations – and that other areas, specifically the Midlands and West, use more peat and turf. Related to geographic location is the factor of availability. For example, a slightly higher percentage of individuals may have access to a natural gas supply in Ennis compared to Athlone, as Ennis came on line earlier. Settlements with natural gas supply predictably have lower CO₂ emissions. For example, the two geographically and size-similar settlements of Portarlington and Edenderry have very different emissions: 3,087kg CO₂ and 3,658kg CO₂ respectively. This is due to the availability of natural gas supply in Portarlington. Natural gas, however, should not be seen as a long-term sustainable alternative to solid fuels.

The per capita EF for domestic energy use (EF Energy, Fig. 3) was then calculated as follows:-

**Equation 1:**

\[
\text{Per Capita EF Energy} = \frac{\text{Per capita CO₂ Emissions}}{\text{Carbon Sequestration Rate (5.2t-CO₂/ha)}} \times \text{Equivalence Factor (1.38)}
\]

This equation was applied to data for all 79 settlements. The EF values were proportional to household energy CO₂ emissions.

From Figure 4, it is evident that EF Energy varies according to location and availability of supply, while Figure 3 shows that population size does not influence the magnitude of EF Energy. Where natural gas from the main grid was available, EF Energy was reduced. Where natural gas was not available, an increase in EF Energy was evident. Where turf peat was frequently used (Midlands), EF Energy was increased further.

In Figure 3, the 22,052-86,998 population size range had the lowest EF Energy score, as it only contained Limerick city, which was connected to the natural gas distribution grid. The size-band 2,700-11,098 contained 12 settlements, of which nine were located in the Midlands or Sligo, where peat is more frequently used.
WATER CONSUMPTION

While measures may be implemented to encourage a reduction in water usage, one of the more pressing issues with regard to water usage is wastewater treatment. The methodology adopted in this section was designed primarily to measure water use for input into EF analyses of settlements. At settlement level, however, EF methodology does not consider on-site wastewater treatment and disposal. Therefore, modifications were made to the methodology, as traditional EF does not adequately point up the environmental burdens associated with increased water use or with increased densities of on-site treatment plants for single houses and housing located in settlements without municipal wastewater treatment facilities.

One of the most important factors influencing groundwater pollution is the density of on-site systems, generally septic tank systems. In 2000, 35–40% of the national average housing stock were using on-site wastewater treatment systems, with the proportion in County Monaghan being 73% (An Taisce, 2003b). One additional house per hectare, each with 4-5 people, can increase nitrate concentration in the area by approximately 15 mg/L NO₃, given that a typical hydraulic loading for a single house of 180 litres (0.18m³) per person per day is assumed (An Taisce, 2003a; Daly & Fitzsimons). Problems can arise in particular where there are grouped housing schemes with both a well and septic tanks (Daly & Fitzsimons, 2003).

METHOD OF WATER USE MEASUREMENT

Domestic consumption accounted for over 60% of the total demand for water in Ireland in 2000 (Atkins, 2000, p1). Two complementary methods were adopted here to estimate per capita consumption (PCC) (Atkins, 2000, p1):

1) Review of previous studies
2) Micro-component analysis

Both methods were utilised, as SFSP1 questionnaire survey results were used to update the micro-component analysis provided in Atkins’ National Water Study (Atkins, 2000). The methodology is loosely based on the National Water Study methodology, which estimated domestic water demand using bottom-up micro-component analysis (Atkins, 2000). PCC values derived in other studies were used to estimate baseline values (Atkins, 2000). PCC may be expected to vary amongst settlements due to differences in water usage behaviour.

Significant influences on level of water use in a household were occupancy rate and “white-good uptake” (Atkins, 2000). SFSP1 questionnaires asked individuals to state the number of household water-related appliances in use, such as dishwashers and washing machines, in order to calculate white-good uptake. Average numbers were calculated for each class of settlement. Aggregation of data into classes improved sample robustness and facilitated calculation of the white-good uptake factor.

The consumption rate for each water usage micro-component (a micro-component includes any household appliance or activity which consumes water, such as a toilet, a sink, or car washing, and is measured in litres per head per day) was calculated as:

\[ U_i \times F_i \times V_i \]

where:
- \( U \) = the uptake; that is, the percentage of households with a micro-component (as a proportion, 0 to 1.0),
- \( F \) = the frequency of use (in times per capita per day), and
- \( V \) = the volume of water used per occasion (in litres) taken from Atkins (2000, p7).

RESULTS

Correlation analysis results did not indicate significant relationships between settlement attributes and water consumption. Figure 5 shows that water consumption increased with increasing settlement population size. Water consumption will vary according to usage habits in different homes. Water consumption may be reduced through the elimination of non-functional water use; that is, running a tap when shaving, operating a dishwasher with only a partial load, and so on. Another potential means of reducing water consumption is through adequate control of residential water pressures without compromising passable flow.
ECOLOGICAL FOOTPRINT OF WATER

Having estimated from the SFSP survey the approximate numbers of households connected to on-site treatment within each settlement, the population was split according to the proportions connected to municipal sewage treatment and to on-site treatment (generally septic tanks). A density of one residence per acre (0.405ha) has been proposed to warrant adequate dilution (Daly & Fitzsimons, 2003). The area required around a dwelling by the Irish EPA is approximately 154m². Therefore, a mid-point value of 0.203ha was selected as a best-guess value. The overall EF for water per capita per settlement was calculated as follows:

\[ S_{ef} = \left( (S_m * S_t) + (S_o * 0.203) \right) / S_p \]

where:
- \( S_m \) = Proportion of people per settlement connected to mains sewage treatment,
- \( S_t \) = Per capita settlement footprint associated with municipal treatment plants,
- \( S_o \) = Proportion of people per settlement connected to on-site treatment,
- \( S_{ef} \) = Per Capita Settlement EF water,
- \( S_p \) = Settlement population.

The results of per capita water consumption and EF Water are not proportional to each other (see Figure 5 and Figure 6). Water consumption is generally greater in settlements with higher population sizes (Fig. 5). This may indicate that people living in larger settlements are more resource-use intensive; that is, they possess and use a greater number of appliances which consume water.

However, the EF of water did not mirror the water consumption patterns shown in Figure 5 (Fig. 6). This was due to the presence of municipal wastewater treatment plants in larger settlements. The remediation area required in EF calculations for on-site treatment resulted in higher scores in smaller-sized settlements. The exception to the trend was the population size band of settlements between 11,099-22,051 persons. At the time of questionnaire distribution, Sligo was still discharging directly to estuarine waters (EPA, 2004b). Sligo therefore contributed considerably to the higher EF score for the size band.

DISCUSSION

Considering the effects of the settlement attributes, population size, service level, geographic location and place in the spatial hierarchy on the five material and energy flows (two of which are explained in this paper), it is possible to identify the areas which need to be addressed most urgently in planning and land use in contemporary Ireland. Table 5 categorises the main settlement attributes according to where they influence the flow variables of transport, energy, waste, water and food.

In MA-SFSP, the comparison of economic and social indicators with EF results across a range of settlement types adds weight to policy considerations. This is because the EFs are not just measurements of human resource demand alone but are related to other aspects of society-environment interactions. The component flows were evaluated based on the significant correlations with settlement attributes.

Spatial representation showed that geographical location was the primary actor with regard to the magnitude of per capita household CO₂ emissions and EF for energy, whilst any relationships with other settlement attributes were incongruous. The Midlands and Sligo clusters had the highest CO₂ and corresponding EF values, whereas the Limerick cluster had the lowest. There were two reasons for this: the first was the availability of natural gas in the Limerick cluster, and the second was the use of peat in the Midlands and Sligo.

Geographic location affects the energy-use type through a series of sub-factors. Supply and availability inevitably dictate choice. Additionally, a substantial number of new households have been built which, being new, are more energy efficient due to technological advancements and better insulation. At the same time, an increase in housing size may offset these energy gains.

Energy supply in Ireland needs to be sourced from more renewable sources in order to reduce the influence of EF energy. It has been proven that increases in industrialisation lead to increases in GDP, which in turn leads to an increase in house size (Medved, 2005). The degree to which improvements in fuel use and insulation influence efficiency remains to be determined. In Slovenia, scenario strategies have shown that an increase in renewable energy use from 6% to 12% decreased the EF by almost 10% (Medved, 2005). This is because the EF of renewable fuels there is only 0.04 gha/capita compared to 0.21 gha/capita for fossil fuels (Medved, 2005).

The enforcement of EC Directive 2002/91/EC on building regulations is suggested. This directive suggests that the performance of buildings should be based on methodologies which take account of building design, air conditioning, heating and the application of renewable energy sources (EC, 2002). Article 5 of the directive suggests the consideration of decentralised energy supply systems and district heating based on renewable energy sources and the use of Combined Heat and Power (CHP) (EC, 2002). CHP is the simultaneous generation of electricity and heat in a single process, creating an energy saving of between 20%-40% over power generation alone. There is a potential market of up to 700MW of installed capacity in Ireland. However, at current levels of investment, the Electricity Supply Board (ESB) predicts that only 65MW of energy supply will be added by 2010. In order to facilitate further CHP generation, favourable fiscal treatment for CHP schemes, exemption from the Public Service Obligation (PSO) levy and amendment of the narrow definition of CHP to allow sufficient support mechanism is required (DETE, 2005; UNEP, 2000).

Table 5. Matrix containing flow variables and settlement parameters. A tick (√) indicates dependence.

<table>
<thead>
<tr>
<th>EF</th>
<th>Size</th>
<th>Functionality</th>
<th>Geographic Location</th>
<th>Place in the Spatial Hierarchy (including growth centres)</th>
<th>Other Factors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td></td>
<td></td>
<td>√</td>
<td>√</td>
<td>Availability which is linked to location</td>
</tr>
<tr>
<td>Transport</td>
<td>√</td>
<td>√</td>
<td></td>
<td>√</td>
<td>Congestion which is linked to size and design</td>
</tr>
<tr>
<td>Waste</td>
<td></td>
<td></td>
<td></td>
<td>√</td>
<td>Collector and/or LA waste management efficiency</td>
</tr>
<tr>
<td>Water</td>
<td>√</td>
<td></td>
<td></td>
<td>√</td>
<td>Appliance intensity</td>
</tr>
<tr>
<td>Food</td>
<td>√</td>
<td></td>
<td></td>
<td>√</td>
<td>Income levels</td>
</tr>
</tbody>
</table>
With regard to the EF of water, the results show that smaller settlements have a negative impact on EF results. The provision of municipal wastewater treatment is essential for the sustainable functioning of all settlements. Planning restrictions would be appropriate for settlements not serviced by municipal wastewater treatment plants.

EU regulations in relation to thresholds for provision of wastewater treatment plants, together with rapid population growth in smaller settlements and small satellite settlements, may result in an additional need for improved wastewater treatment. Population growth in settlements under 2000 PE may create a threat to surface and groundwater quality, as the Urban Waste Water Treatment Directive 91/271/EEC does not stipulate the need for wastewater treatment systems for these settlements in the near future. For example, two settlements of 1,500 persons each will not require the installation of municipal secondary treatment systems. However, one settlement of over 2,000 persons will require such a treatment system.

The EFs for each component flow were aggregated to give an Overall EF. However, no significant relationships were found between the Overall EF for the 79 settlements and the settlement attributes of population size, functionality, position in the spatial hierarchy and geographic location. The EF Overall variable did correlate positively with EF Waste and EF Energy, p <0.01 (r = 0.431) and p <0.01 (r = 0.344) respectively. Both waste and energy flows were shown to be influenced by geographic location. For waste flow, location is related to the fact that waste management efficiency varies spatially and, for energy, location is connected to availability and cultural habits. Therefore, these flows may independently act as signals, indicating settlements with low environmental service levels and potentially high overall EFs.

Settlements are different, and the path towards more sustainable development will vary between settlements (Uzzell et al., 2002). The same solution might not be applicable to systems characterised by different use patterns and demand (Federici et al., 2003). The linking of the EF results to their associated settlement attributes, reported here, represented an attempt to bring together socio-economic and environmental concerns. An understanding of the fundamental character of interactions between society and the environment forms part of the process of creating a new dimension to sustainability thinking (Haberl et al., 2004). Thus, by linking concept to reality, the work reported here has created a framework for policy direction.

In order that complex systems be examined, a case-by-case, settlement-by-settlement application is required (Crabtree, 2005). Similarly, the variations in EFs in some settlements compared to others, as reported here, are due to reasons related to a range of settlement attributes whose influences vary enormously between settlements and between flow types. The specific reasons for the EF performance of each settlement therefore considered the component EF scores rather than the Overall EF score. Careful consideration of the components of the footprint help to evaluate the relative ecological cost of various human activities, enabling policy analysts to identify ‘hotspots’ for policy action (McDonald & Patterson, 2004).

**CONCLUSION AND EVALUATION**

With regard to household energy use and the EF associated with energy use, the following can be concluded:-

- Spatial representation using GIS showed that geographical location was the primary driver with regard to the magnitude of per capita household CO₂ emissions, whilst other relationships with settlement attributes were unclear.
- While natural gas is not a long-term sustainable option, extending its distribution to settlements in the medium term may be expected to lead to a significant reduction in CO₂ emissions.
- The more rapid exploitation of alternative technologies, including combined heat and power, solar and wind energy generation, through regulation or promotion, will minimise reliance on hydrocarbons and reduce CO₂ emissions.

With regard to household water consumption and the EF associated with wastewater, the following can be concluded:-

- More water per capita is consumed in larger settlements.
- EFs were higher in settlements with lower proportions of households connected to municipal wastewater treatment.
- The higher EFs found in smaller settlements indicate a possible need for restriction of development in smaller settlements where municipal wastewater treatment is not required under existing legislation.

Overall, the relative sustainability of settlement types was found to be closely related to a set of quantifiable settlement attributes. Critical parameters affecting the progression of sustainable development in Irish settlements cannot be simply listed in order of importance but should be considered as equal parts of an overall system. For example, geographical location will influence energy and waste patterns but is not an issue with regard to water use patterns.

Development policies for settlements must facilitate development which satisfies institutional and physical design parameters promoting systemic application of socio-economic and environmental justice, in order to be considered sustainable. Metabolic flow variables have a crucial role to play in sustainability appraisal at settlement level and can provide an invaluable tool in policy-making in the future.

**REFERENCES**


W.S. Atkins, Dublin 17, Ireland.


Equivalents greater than 500 Persons. Environmental Protection Agency, Wexford.


INTERNET REFERENCE

IDENTIFYING OPPORTUNITIES FOR URBAN SUSTAINABLE DEVELOPMENT IN IRELAND: DEVELOPMENT OF SUSTAINABILITY INDICATORS AND INDICES

John Morrissey, Walter Foley, Bernadette O’Regan and Richard Moles

ABSTRACT

Sustainability and Future Settlement Patterns in Ireland (an Irish Environmental Protection Agency-funded project) investigated the relationships between settlement size, functionality and geographic location and sustainable development. Analysis was carried out on a representative sample of 73 Irish settlements, located in three regional clusters. Final research output will provide information for National Spatial Strategy planners, key stakeholders in the research. One aspect of the research was the development of a structured and comprehensive set of indicators and indices of sustainability. A set of forty indicators in four specific domains was selected and developed for the study settlements: ten Environment indicators, ten Quality of Life indicators, ten Socio-economic and ten Transport indicators. In this way, developed indicators cover important aspects of sustainable development, environmental quality, equity and quality of life issues, as well as incorporating an area of pressing concern for the stakeholders, and for future settlement in Ireland, in Transport. Sustainability indices were evaluated through derived aggregation of indicators, to provide empirical summaries of the various aspects of sustainable development investigated. Final indicator and index presentation is achieved using GIS technology, to provide an easily queried and interpreted tool for stakeholders. Forthcoming from analysis has been the identification of attributes of settlements preventing, impeding or promoting progress towards sustainability. This output enables the prioritisation of actions to enhance the sustainability of Irish settlements. The empirical analysis of settlements by these methods enables production of practical recommendations regarding the integration of sustainability goals with Irish settlement planning for the future.

Key words: settlements, sustainability, indicators, indices, GIS

INTRODUCTION

This paper describes methodologies adopted and tailored to assess the sustainability of Irish settlements, with regards to a selected set of attributes. Sustainability of Irish settlements was assessed with regards to settlement size, functionality and geographic location. Metrics adopted, including indicators and sustainable development index modelling, proved to be appropriate and effective. These were applied as part of the University of Limerick (UL) research thesis ‘Appraisal of the sustainability of Irish settlements using indicators and sustainable development index modelling,’ which itself was part of an Environmental Protection Agency (EPA) study entitled Sustainability and Future Settlement Patterns in Ireland. Analysis identified opportunities for enhanced sustainability in a number of broad settlement classes. This paper has the following objectives:

– to provide a background of the sustainable development concept;
– to describe the issues with current urban development in Ireland;
– to provide an overview of methodologies used to assess urban sustainability in Ireland;
– to summarise methodological conclusions regarding the use and applicability of indicators and sustainable development index modelling.

SUSTAINABLE DEVELOPMENT

Sustainable development may be seen as a process of change in which full development potential is reached (Sousan, 1992). Sustainability has become a core element of policy documents of governments, international agencies and business organisations (Mebratu, 1998).

“Sustainability may be defined as a dynamic balance among three mutually interdependent elements: (1) protection and enhancement of natural ecosystems and resources; (2) economic productivity; and (3) provision of social infrastructure such as jobs, housing, education, medical care and cultural opportunities.” (Bell & Morse, 1999)

Practical sustainable development is ultimately concerned with combining, balancing or trading off aspects of these economic, social, environmental (and institutional) dimensions (Mazza & Rydin, 1997). Sustainable development could therefore be described as a process by which economic, social, environmental and institutional policies are aligned so as to be mutually supportive (UNCHS, 1994). As centres of origin of environmental impacts, urban settlements, therefore, must also be seen as the motors of sustainable development (Rees & Wackernagel, 1996; Rotmans et al., 2000).

“The key issue is not ‘sustainable cities’ but cities whose built form, government structure, production systems, consumption patterns, waste generation and management systems are compatible with sustainable development goals for the city, its wider region and the whole biosphere.” (Marcotullio, 2001)

According to Mazza & Rydin (1997, p1), efforts for sustainability should be concentrated in urban environments, due to need to focus sustainable development locally. Sustainable development is not directly observable. It needs to be defined before it can be visualised and studied.
Sustainable development may be defined as a process that enhances well-being by means of improvement in economic and social conditions, allied to protection and enhancement of environmental quality, while minimising environmental impacts elsewhere. An urban settlement may therefore be seen as being sustainable in nature if sustainability criteria are met within the settlement, and if the settlement does not create an excessive drain on environmental resource bases elsewhere.

SUSTAINABLE SETTLEMENTS IN IRELAND

By 2002, approximately 60% of Ireland’s population lived in combined settlements and suburbs of more than 1,500 inhabitants; the other 40% lived in small villages and in the open countryside (CSO, 2003). Economic growth has exacerbated long-running trends of increasing spatial concentration of population and activity (O’Farrell, 1979). The rapid economic expansion of recent times has been accompanied by various problems, such as congestion (Mega, 1995) and delays in the provision of required new infrastructure, such as transport and environmental infrastructure and adequate housing supply (Ellis & Kim, 2001). The trends of urbanisation and an expanding population continue to create a concentration of demands on Ireland’s physical infrastructure and environmental quality nationwide (Lehane et al., 2002). The OECD identifies issues such as transport and urban sprawl as growing problems (internet reference 1). At the beginning of the 21st century Irish national population concerns are therefore focused on questions of achieving optimal balance of population distribution, and particularly concerns with the primacy of the GDA (NESC, 1997).

The urban-rural interface around large towns and cities are noticeable pressure areas in terms of population, planning and environmental impacts (Duffy, 2000). Urbanisation effects are evident in rural areas with ease of access to major urban centres, as well as the suburbs and environs of towns (NESC, 1997). Certain rural areas in proximity to large urban centres have also come to exhibit markedly urban characteristics (Brady, 2000). In addition, the growth in commuter settlements in the vicinity of major urban centres has been a feature of urban growth (Brady, 2000), and the main urban centres have expanded their fields of influence, with an increase in longer distance commuting (NESC, 1997).

Figure 1 shows the percentage increase of population per District Electoral Divisions (DEDs) in Ireland between 1996 and 2002. High rates of increase may be seen around the major urban centres of Cork, Limerick and Galway, with the increase in DED population in Leinster and surrounding Dublin being particularly striking, together with the population decrease in many rural areas.

As evident from Figure 1, rural areas outside of the main commuter zones surrounding larger urban centres face vastly different problems to those faced by rural areas in close proximity to urban centres (NESC, 1997). Rural areas outside of the influence of major urban centres continue to lose population, with shortage of available finance to maintain and improve physical and social infrastructure (EPA, 2000). Peripheral, economically lagging regions may be identified by characteristics such as long-term unemployment, education deficit, growing poverty and outward migration of economically established residents (Portnov & Pearlmutter, 1999).

Ireland therefore faces a number of important environmental issues. Urban sprawl, housing construction and associated transport infrastructure are areas of concern as key environmental pressure sources (Lehane et al., 2002). Overall, issues including infrastructural deficits, transport, housing, urbanisation and national growth imbalances are highlighted by the NDP as weaknesses which the Irish economy and urban structure need to overcome to ensure continued economic and social progress (NDP, 1999b).

SUSTAINABLE AND FUTURE SETTLEMENT PATTERNS IN IRELAND

A pilot study entitled Methodologies for the Estimation of Sustainable Settlement Size (MESSS), which was undertaken by the Centre for Environmental Research (CER), University of Limerick (UL), from March to August 2001, drew initial conclusions concerning the relationships between settlement size (measured by population) and sustainable development (quantified through indicators) (Moles et al., 2002; O’Regan et al., 2002).

Following the completion of this study, funding was provided by the Environmental Protection Agency of Ireland, under the Environmental Research Technological Development and Innovation (ERTDI) programme, to provide further, more comprehensive analysis of the relationships between Irish settlements and sustainable development. The three-year University of Limerick (UL) study titled Sustainability and Future Settlement Patterns in Ireland (SFSPI) establishes means of consolidating and reinforcing the strengths of urban and rural areas nationwide by investigating key aspects of sustainable development and spatial planning. This research will ultimately provide input to the National Spatial Strategy (NSS), a twenty-year planning framework proposed to achieve more equal social, economic and physical development along with balanced population growth in Ireland (NDP, 1999a). Sustainability and Future Settlement Patterns in Ireland therefore investigates the influence of key factors such as urban size, function and geographic location (within
wider spatial networks) affecting progress towards sustainable
development of Irish settlements. Developed indicators and indices
were analysed using these important control criteria, providing an
empirical overview of sustainable development in an Irish context, and
using indicators tailored specifically for Irish settlements.

**METHODOLOGY**

**USE OF INDICATORS**

Indicators are important tools for translating and delivering concise and
scientifically credible information (Lehane, 1999). Indicators may
provide a simplification of complex phenomena (OECD, 1997), with
successful indicators translating information in a manner that can be
readily understood and used by decision-makers (Lehane, 1999).

Indicators have a valuable role to play in the future of sustainable
planning for urban areas. Key urban environmental indicators can help
policy-makers and the public to track sustainability more effectively
(Pender et al., 2000).

It may be seen therefore that indicators attempt to quantify aspects
of sustainability in order to assess conditions, trends and performance.
However, a limitation of indicators is that the whole of human
experience cannot easily be measured and rated. Indicators, therefore,
may not illustrate the full complexity of the systems or processes they
represent (Smeets & Weterings, 1999). A degree of simplification is a
prerequisite, however, to providing information in a form of practical
use to decision-makers and understandable to the community (Kelly &
Moles, 2002).

Indicator development also requires good quality data, which needs
to be updated at regular intervals. This makes indicators particularly
dependent on availability of data (Lehane, 1999). A lack of data may
mean that critical indicators are omitted, or issues of importance are not
addressed. Factors of significance may therefore be omitted from the
policy formulation process (OECD, 2000). To date, indicators have
been developed under all fourteen ideal indicator categories.

**DATA COLLECTION AND GENERATION**

Fourteen ideal indicator categories were identified by MESSS as the
optimal means of assessing sustainability for settlements in an Irish
context. These were adopted as a starting point for this research, with
data sources previously used in the pilot study investigated for
indicator development for each of the study settlements. A Microsoft
SQL server database was constructed to collect available data and
further identify missing data. All available data sourced from various
reports, publications, government agencies, local authority departments
and other responsible bodies were collected and inputted to this
database (see Table 1).

Data availability matrices were generated for study settlements, in
addition to lists of data gaps for which no known source of information
existed. A questionnaire was developed to fill these data gaps, which
asked questions designed to generate indicators in each of the fourteen
categories described in Table 1. Questions covered topics such as travel
habits, resource use and waste generation, for example.

The questionnaire was distributed to households in each of the
study settlements. Data generation took place in two rounds, from
September '02 to March '03, which constituted round one, and from
March '04 to June '04, round two. In total, 8,740 questionnaires were
distributed, with a 39% response rate by September '04. Returned data
were inputted into an SPSS database for analysis, and summarised to a
settlement level. These data were integrated with any collected data to
settlement level and a list of candidate indicators was constructed.

**Table 1. List of Ideal Indicator Categories.**

<table>
<thead>
<tr>
<th>Ideal Indicator Category</th>
<th>Ideal Indicator Category</th>
</tr>
</thead>
<tbody>
<tr>
<td>Waste</td>
<td>Biodiversity</td>
</tr>
<tr>
<td>Water</td>
<td>Education</td>
</tr>
<tr>
<td>Transport</td>
<td>Income</td>
</tr>
<tr>
<td>Energy</td>
<td>Housing</td>
</tr>
<tr>
<td>Resource Consumption</td>
<td>Employment</td>
</tr>
<tr>
<td>Air</td>
<td>Health</td>
</tr>
<tr>
<td>Noise</td>
<td>Access to Services</td>
</tr>
</tbody>
</table>

In order to investigate the key influences of size, functionality and
geographic location on the progress of Irish settlements towards
sustainable development, the following were selected as the independent control variables:
- Population size 2002
- Percentage population change from 1996-2002
- Distance from nearest Gateway (km) settlement
- An Index of Tertiary Services per settlement (Services Index)

**RESULTS**

**DEVELOPMENT OF INDICES**

**Indices**

A set of aggregated indicators, combined mathematically or through
weighting, is termed an index. An index may be used to greatly
simplify the information contained in its constituent indicators (Pagina,
2000). A single Sustainable Development Index (SDI) has the benefit
of aggregating various measurements into a comprehensive overall
index, and of demonstrating overarching trends in simple presentations
(Pagina, 2000). Aggregated indicators may therefore be referred to as
“executive summaries of complex realities” (Working Group on
Environmental Information and Outlooks, 2002, p10). The process of
aggregation of two or more indicators to form an index is described by
the OECD (WGEIO, 2002). This process was followed in the
development of a Sustainable Development Index for Irish settlements,
as described in Table 2 and Figure 2.

**Selection of suitable indicators**

A final set of 40 indicators of sustainable development was selected
from a candidate list of 150 indicators, using criteria such as indicator
applicability and relevance, normal distribution of data and full data
availability for all settlements. These 40 indicators were subsequently
divided into four groups or domains (Table 3). These were
Environment, Quality of Life, Socio-economic and Transport. These
domains cover the key sustainable development bottom-line
triumvirate of Environment, Economy and Society, as well as
incorporating Quality of Life and Transport aspects, domains which
cover issues of immediate concern to the NSS. In this way, sustainable
development concerns from the point of view of the major stakeholders
(being the NSS and EPA) are addressed. The selected indicators
represent the best means of assessing sustainable development for Irish
settlements. Indicators follow from the MESSS list of ideal indicators
and cover those identified indicator categories to the furthest possible
extent, given data availability and the resources available to the
research team (see Table 3).

**Index development**

Sustainability indices were developed for study settlements from the
aggregation of selected indicators deemed suitable for use. Four
separate indices of sustainable development were developed, covering the domains of Environment, Quality of Life, Socio-economic and Transport. A simple weighting system was most appropriate for indicator aggregation, to enable simple and transparent data aggregation. This enables discourse and exchange of ideas and perspectives among non-technical stakeholders from differing backgrounds, a crucial output from this research.

From the data transformation step, all 40 indicators (in the four domains) were given a value between 0 and 1 for each study settlement, through the application of a normalisation function. Indices were then developed by aggregating the 10 constituent transformed indicator scores of each domain to develop a corresponding index for that domain. A final index of sustainability was developed, through further aggregation of the four developed indices into a final figure.

The final stage in index development involved incorporating a graphical representation of the constituent indicator scores of each developed index. This graphical presentation of sustainable development required the presentation of the nature of trade-offs and compromises required for sustainable development of settlements. This
was achieved by developing what have been called “cobweb” diagrams. These graphs were generated in Microsoft Excel software from indices scores for each settlement, and are based on techniques described by Bell & Morse (1999). Cobweb diagrams present an easily readable and accessible evaluation of the level of sustainable development of a settlement, through proportionally representing index scores in a specific surface area pattern. Graphs show each index score out of 10 for all developed indices for all study settlements, together with the final SDI score, out of 100, also for all study settlements. The make-up of these scores is graphically illustrated by each graph. Each index is made up of 10 indicators, scored on a scale of 0-1, with 0 being the least sustainable state and 1 being the most sustainable state. These scores are summed for each index, giving a final score out of 10. Graphs therefore illustrate indicators contributing most or least to the overall score for each developed index. In this way, the simplification from indicator aggregation need not hide underlying complexities, and a presentation representing the trade-offs inherent in sustainable development policy formulation to decision-makers is generated. Similarly, the final SDI score out of 100 is comprised of scores from each of the component indices, Environment, Transport, Quality of Life and Socio-Economic. Kite diagrams illustrate where the SDI index score comes from, as with the diagrams for individual indices. Figure 3 presents the cobweb diagrams developed for each index for Athlone, together with the kite diagram for the overall Sustainable Development Index (see Figure 3).

CONCLUSIONS

METHODOLOGICAL CONCLUSIONS

• The sample size of 73 settlements covered all settlement types in Ireland (apart from Dublin) and is representative of the urban environment in the currently rapidly changing Ireland. The analyses were carried out using best available quantitative methodologies.

• Resources and time dedicated to data collation and collection proved crucial. Analysis identified clear patterns linking settlement attributes to the level of sustainability achieved and this was forthcoming from the full dataset assembled.

• Metrics to measure urban sustainability were developed, adapted and tested, and these have proven to be applicable to the sustainability appraisal of Irish settlements, and of real-world use to policy and decision makers.

• The relative sustainability of settlement types was found to be closely related to a set of quantifiable attributes of settlements.

• All indicators and indices were developed based on the extensive data collected and generated. These data were assessed through a number of stages to determine the most suitable data for indicator development, in terms of indicator applicability and relevance, normal distribution of data and full data availability for all settlements. All conclusions are therefore evidence based, and can be examined and argued on this basis.

• A larger number of settlements was included in this study than in any previous appraisal of sustainable development in Ireland. Because of the number of settlements included, trends on a bigger scale have been discernible from analysis. Conclusions are therefore more applicable to the country as a whole.

• From a complicated and inter-related set of findings, as was anticipated from the outset, general overarching patterns and trends were detected from indicators and indices which were not previously obvious.

• Overall, time and resource limitations together with data gaps were the greatest impediments to the work. These necessarily constrained the scope of the work.

OUTPUTS FROM THE RESEARCH

In conclusion, the research achieves the following:

• Developed indicators, organised under the DPSIR framework,
provide a structured, comprehensive and meaningful measurement of the level of sustainability of selected Irish settlements.

- Indicators were developed covering four broad domains. Quality of life, equity and environmental protection issues are identified as key areas of concern from the point of view of sustainability. These were addressed therefore in the domains of Quality of Life, Socio-economic and Environment. A fourth domain of Transport addresses the key research question of transport issues identified by the MESS pilot study. In this way, it can be seen that developed indicators of sustainability are tailored to suit the requirements of the stakeholders who will be using them, in this case planners and decision-makers.

- Settlements were assessed with respect to their progress towards (or away from) sustainability, in terms of size, function and geographic location.

- Indicators were aggregated to formulate indices, to make the research findings more user-friendly for stakeholders. The development of indices enables ranking of settlements in terms of progress towards sustainability, as well as identifying interconnections between indicators.

- A single Sustainable Development Index (SDI) for Irish settlements was developed.

- Developed indicators and indices were presented in a user-friendly GIS package, for ease of use and accessibility by stakeholders. This enables the spatial presentation of findings and a readily accessible means of storing and examining indicator data.

- Critical parameters important in progressing sustainable development for Irish settlements were identified.

- Practical recommendations were forthcoming from research findings regarding the integration of sustainable development considerations in Irish settlement planning, within the NSS and Regional Planning Authorities.

REFERENCES


INTERNET REFERENCES

IRELAND’S ECOLOGICAL FOOTPRINT 2003: APPLYING AN AREA-BASED INDICATOR OF SUSTAINABLE DEVELOPMENT

Conor Walsh, Bernadette O’Regan and Richard Moles

ABSTRACT

Ireland’s recent economic development has spurred increasing energy use, private transport and waste generation. In light of this, the need to measure and gauge the extent to which Ireland is becoming less sustainable is seen as more important to policy makers. The primary aim of this study is to estimate the extent to which Ireland’s bio-capacity demand exceeds global bio-capacity provision. The ecological footprint is an aggregate sustainability indicator that translates consumption categories into the area (assuming global productivity) required to satisfy consumption and sequester wastes. The calculation method applied deviates from current standardised practice by applying novel conversion factors, incorporating, where possible, Irish data. While much effort has been made to standardise footprinting at an international level to facilitate international comparisons, it is also important to improve existing methods by experimenting with different data sources and conversion factors. Here, data used were derived from both top-down and bottom-up sources. The results indicate that an average Irish individual requires approximately 5.8 global hectares. The largest single component is energy land, for which it is estimated that 3.1 global hectares per capita (gha/cap) are needed to satisfy domestic energy consumption. The area of crop and pasture required was calculated as 1.6 (gha/cap). The per capita footprint of forest products required half a global hectare. Sub-components such as waste and transport are also calculated. The main implication of the results is that the footprint will be difficult to reduce given that oil consumption (due to high levels of car use) and cattle production form a global hectare. Sub-components such as waste and transport are also calculated. The main implication of the results is that the footprint will be difficult to reduce given that oil consumption (due to high levels of car use) and cattle production form a considerable challenge. Future research in footprinting in an Irish setting should attempt to further incorporate Irish specific factors and reduce the hypothetical nature of the footprint.

INTRODUCTION

One of the initial criticisms levelled against sustainable development as a concept was the fact that it would prove too difficult to apply in a practice. The fact that the original Brundland definition (World Commission on Environment and Development, 1987) encompasses social, economic and environmental dimensions means that theoretically there is little that would not fall within its remit. It could be argued that environmental indicators, such as levels of pollution, would facilitate the application of the concept in decision-making. However, such indicators focus on the end result of human activity and can only be compared against, at best, a situation with no emissions or, as is more likely, a situation with reduced emission levels. Using an indicator such as this, it becomes difficult to determine if such an activity can be sustained indefinitely. Any cursory evaluation of research undertaken worldwide will show studies that quantify pollution estimates to many decimal places. The distinguishing factor for a sustainability indicator is that it implies a quantifiable estimate for what can be sustainably maintained (Morse et al., 2001). There have been many attempts to develop indicators of sustainable development; these include the genuine progress indicator (Lambert, 2005) and the concept of material intensity per unit of service (MIPS) which provides an estimation of the real impacts and returns from industrial production (Schmidt-Bleek, 1994). None of these to date has received universal support.

AN AREA-BASED INDICATOR OF SUSTAINABLE DEVELOPMENT

The ecological footprint was developed in the early 1990s by Mathis Wackernagel and William Rees from the University of British Columbia. Simply put, the ecological footprint estimates the land area required to produce the majority of resources consumed by a population as well as sequester the wastes generated. Typically a footprint will contain an element that accounts for energy use, such as the newly forested area required to sequester carbon dioxide emissions, the arable land required to grow the vegetable products consumed as well as the pasture required. A footprint will also contain the forest area required to provide wood products as well as the area of sea surface required to produce the fish consumed. General practice is to use average global yield and equivalence factors to express the footprint in ‘global hectares’ (gha), units that represent average global productivity (Wackernagel & Rees, 1996).

In order to live sustainably, the total resource demand imposed by human consumption must not exceed the total bio-productive land area. This global earth-share is approximately two hectares per person, and by comparison with this earth-share the extent to which a lifestyle is sustainable can be gauged. Where the earth-share is exceeded, it is argued that we are living in ecological deficit as development is being fuelled by natural capital rather than regenerative bio-capacity. To summarise, the ecological footprint moves sustainability as a concept away from purely theoretical study and into the arena of applied research.

COMPONENT VERSUS COMPOUND FOOTPRINT

The footprint calculation method has been updated and modified since its original development. This has resulted in the emergence of two main types of calculation, namely component and compound footprinting. Compound footprinting is often referred to as a “top-down” approach.
since it is best suited to national scale footprinting (Chambers et al., 2000). Calculations are based on trade data: consumption is defined as imports plus production minus exports (and, if data are available, plus or minus stock changes). These are normally expressed in aggregated categories which incorporate resource demand figures without accounting for every single end use. The most prominent examples of the compound approach are the national footprint accounts produced periodically by the Global Footprint Network. Component footprinting has been widely used in recent years as professional experience of footprinting and technical competence develops in tandem. Component footprinting may be defined as "bottom-up." Consumption and emission estimates are still the basis for the footprint. However, these are calculated using more comprehensive disaggregated data on consumption divided into 'components' (Simmons et al., 2000). Often, features of life-cycle analysis, such as detailed embodied energy estimates, are applied in component footprint estimates. Compound footprinting is concerned with aggregated resource consumption, while component footprinting focuses on activities. Instead of labelling the methodologies as "top-down" and "bottom-up," perhaps a more accurate description might be "outside-in" and "inside-out."

ADVANTAGES AND DISADVANTAGES OF FOOTPRINTING

The main advantage of footprinting in general is that it allows immediate, evidence-based comparison of the level of sustainability between areas, individuals and points in time. The primary advantage of compound footprinting is that (at least at national scale) trade data are usually available (Senbel et al., 2003). Sub-national footprinting accounts can be calculated using a proxy such as population size. The main disadvantage is that compound footprinting can over-simplify consumption categories, and often fails to account for region-specific factors. The obvious advantage of component footprinting is that it is based on a detailed and complex dataset. The disadvantages of component footprinting are its complexity and large data needs, which means having to address more complex issues. It has been commented that a disaggregated footprint can reduce the communicative value of the overall result. Van den Bergh & Verbruggen (1999) make the point that footprints are largely notional, representing hypothetical rather than actual land use, as is demonstrated by the fact that a global footprint can exceed the global area. There is the danger that footprints are taken to be valid measures of actual land areas required, and this leads to interpretational difficulties.

The main aim of this paper is to explain how a footprint was calculated for Ireland by adopting a novel method which takes account of Irish conditions. The result is therefore not directly comparable with footprints published for other nations (Leh & Wackernagel, 2004). There have been recent attempts at international level to standardise footprint calculation. While many of the footprint calculations in this study are based on standard methods, there are notable differences, particularly in relation to pasteurland. It is argued that the method adopted here provides more useful information for Irish decision-makers.

METHODOLOGY

The calculation methods adopted in this study are taken from both compound and component footprinting. Decisions as to the most appropriate method to adopt were made on the basis of (a) appropriateness to Irish conditions and (b) data availability. Each main category is addressed separately.

ENERGY

Energy footprints were calculated using a dual approach. Information was based on the energy balances provided by Sustainable Energy Ireland (SEI). Energy imports, production and exports were expressed in tonnes of oil equivalent. Using these estimates the overall consumption or primary requirement of energy within the state was calculated. This represents a compound estimate. However, the energy balance allows further desegregation into different components such as industry sectors, transport, domestic energy and agriculture. Emission factors provided by Sustainable Energy Ireland were applied to translate energy consumption into carbon dioxide emissions. These allowed consumption values (given in terms of tonnes of oil equivalent) to be translated into carbon dioxide emissions and subsequently bio-productive area. An example of the calculation for sod peat is shown below:

- Tonnes CO₂ = (1,000 Ktoe x 1000) x 3.67 tonnes CO₂ toe⁻¹
  = 3,670,000 tCO₂
- Eco Footprint (gha) = (3,670,000 tCO₂ x 0.69 x 1.35 gha ha⁻¹) / (0.95 tC ha⁻¹ yr⁻¹ x 3.66 tCO₂ tC⁻¹)
  = 983,205 gha

Conversion factors used by the Global Footprint Network (GFN, 2005) were applied to translate carbon emissions into the area of new forest required to sequester it.

TRANSPORT

Transport footprints generally comprise the land area required to sequester vehicle engine emissions in the same manner as shown above, as well as indirect emissions from maintenance and manufacture (the ‘uplift factor’). Car transport forms a significant part of the transport footprint. An estimate for car kilometres on national roads was calculated from data in the National Roads Authority (NRA) National Roads and Traffic Flow Report for 2003. Information on the vehicle kilometres for the non-national road network was unavailable and, therefore, a multiplier based on the existing figure was needed. The Goodbody Report (2001) estimates that urban and highway traffic account for approximately 40% of car kilometres. The recent urban development in the east of the country has led to suggestions that this is potentially an underestimate. Thus, an arbitrary division of 50% for national and non-national roads was applied to estimate national car kilometres. The emission estimate was derived from the SEI report Analysis of New Car Registrations 2000 (Howley et al., 2003). An estimate for carbon dioxide emissions per engine size for both diesel and petrol engines of new vehicles was then applied to the engine size distribution of the national fleet supplied by the Irish Bulletin of Vehicle and Driver Statistics 2003 (Department of Environment, Heritage and Local Government, 2004). A national division of 86.5% for petrol and 13.5% for diesel was used for each engine size category. The final emission factor of 168 gCO₂/km was used in conjunction with the overall estimate of car kilometres to approximate the total carbon emissions. An additional 51% was included to account for indirect emissions (Moffet & Miller, 1993) and the total carbon footprint was calculated in the same manner as shown above.

Emissions for public transport were estimated on the basis of information on vehicle emissions and fuel efficiency obtained from Bus Éireann and Iarnróid Éireann. For indirect energy requirements, a report entitled the Energy in Freight Transport (Congressional Budget Office, 1982) gives an uplift factor of 57% of propulsion fuel used.
Data availability on commercial vehicles is generally poor. Freight data from the Eurostats database were used in conjunction with emission estimates provided by the UK Emissions Database. This assumes an equal number of rigid and articulated vehicles and an average speed of 70km/hr.

**FOOD AND AGRICULTURE**

The food footprint was calculated following a standard method. Separate estimates for importation, production and exportation of foodstuffs were calculated based on trade data provided by the Central Statistics Office (CSO, 2005). For commodities such as vegetables and cereals, the global yields can be used directly. For other commodities such as compound foods (such as pastries), conversion factors taken from Barrett et al. (2002) were applied. The equivalence factors used in the Living Planet Report 2004 (Loh & Wackernagel, 2004) were used to convert pasture or cropland areas into global hectares. An example of the calculation is given below:

- 1 tonne of beef requires 41.75 ha of direct land
- 41.75 ha tonne⁻¹ x 0.48 g/ha = 20 g/tonne

A different approach was taken to pasture footprinting. Standard method is to apply a conversion factor based on tonnes of meat consumed. While this accounts for the fact that slaughtered livestock consumes biomass before the year of consumption, it does not account for the standing stock (animals not slaughtered). Using data from the Department of Food and Agriculture (2004) and CSO (2004), the method adopted here accounts for both animals slaughtered in 2003 and those still living at the end of 2003. It assumes that the total size of the national herd does not vary greatly from year to year. Example:

- In February, 4,414 beef cattle less than 1 year old were slaughtered in a factory. This translates into 8,828 feed months.
- Dividing by 12 gives an estimate of 736 feed year equivalents. This equates to 441 tonnes of grass, 368 tonnes of silage and 184 tonnes of concentrate (based on Table 2).
- 441 tonnes of grass/7.83 tonnes ha⁻¹ = 56 ha
- 368 tonnes of silage/5 tonnes ha⁻¹ = 77 ha

Teagasc provided unpublished estimates of silage yields, and grass yields were estimated based on the application of nitrogen fertiliser. Animals alive at the end of the year are assumed to eat a year’s worth of feed. This method was applied to both cattle and sheep. The footprint of pig meat was calculated by applying a conversion factor that estimated the amount of feed required to feed the breeding animals (i.e. sows) as well as those slaughtered. This conversion factor (3.75 tonnes feed/tonnes pork) was applied to tonnes of slaughtered pork, using data provided by the CSO. Since the majority of poultry slaughtered are relatively young, a simple conversion based on live weight equivalent was applied. It should be noted that a portion of the imported animal feed footprint (mostly in the form of imported oil crops), a portion of domestic grain footprint and a portion of the pasture footprint was subtracted from the overall estimate since the majority of the livestock it feeds is eventually exported as this is considered to be no longer part of Ireland’s footprint. The footprint of forestry was calculated by converting the traded tonnes of wood products into round wood equivalents. This was supplemented by production estimates provided by Coillte. Chambers et al. (2004) provided the global yield factor estimate.

**WASTE AND WATER FOOTPRINTING**

Waste footprints were calculated by quantifying the carbon emissions created to produce the material waste. Since recycled material often requires less energy to process than virgin material equivalent, it has a reduced embodied energy footprint. Data from the EPA Interim Waste Database Report 2003 (EPA, 2004) were used along with embodied energy estimates from a number of sources, whereby an average value for the various material categories was calculated and applied. An estimate for the carbon intensity of energy was calculated by dividing the total carbon dioxide emissions by the final energy requirement. This resulted in an estimate of 0.019Kg C/MJ. This allowed the energy estimate to be converted into carbon estimates and ultimately a footprint value, in the same manner as described above. An attempt was also made to estimate the amount of fuel used in waste transportation.

The footprint of water use was calculated using 30-year rainfall estimates provided by Met Éireann. These were used to calculate the average amount of water entering the hydrological system from an average hectare. In order to account for plant life and climate conditions, the effects of evapotranspiration, taken from Burke et al. (1989), were included in the calculation. Information on treated water provided to non-domestic sources, together with domestic use rates and number of houses, all from the 2002 Census (CSO, 2003), was used to estimate water use.

**RESULTS**

**ENERGY**

The direct energy estimate (excluding marine bunkers) results in an estimate of over 12 million global hectares or 3.1 global hectares (gha) per person. Figure 1 demonstrates that the majority is comprised of imported oil. If the embodied energy of traded goods is taken into account, this figure increases to 3.13 gha/capita. This is due to the fact that Ireland is a net importer of commodities. However, the export footprint is significant as Ireland has a higher carbon intensity than the global average and exports (such as meat and fish) tend to have higher embodied energies. It should be noted that the footprint represents primary energy requirement; thus, only the fuel used to produce electricity is accounted for. The entry for electricity in Figure 1 represents imported electricity.

In relation to energy use in industrial sectors (see Table 1), results indicate that the food industry has the largest footprint. Other energy sectors have also been calculated, as shown in Table 2. A striking feature of these results is the large contribution made by transport: the

![Figure 1. Summary of Energy Footprint by Primary Energy Category.](image-url)
### Table 1. Industrial Energy Consumption and Associated Footprint

<table>
<thead>
<tr>
<th>Industry</th>
<th>(000 TOE)</th>
<th>Footprint Gha</th>
<th>Gha/capita</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iron and Steel</td>
<td>9</td>
<td>7719</td>
<td>0.00</td>
</tr>
<tr>
<td>Chemical</td>
<td>451</td>
<td>447500</td>
<td>0.11</td>
</tr>
<tr>
<td>Non-ferrous Metals</td>
<td>30</td>
<td>54535</td>
<td>0.01</td>
</tr>
<tr>
<td>Non-metal Minerals</td>
<td>362</td>
<td>424311</td>
<td>0.11</td>
</tr>
<tr>
<td>Transport Equipment</td>
<td>14</td>
<td>18762</td>
<td>0.00</td>
</tr>
<tr>
<td>Machinery</td>
<td>116</td>
<td>189811</td>
<td>0.05</td>
</tr>
<tr>
<td>Mining</td>
<td>74</td>
<td>85350</td>
<td>0.02</td>
</tr>
<tr>
<td>Food, etc.</td>
<td>514</td>
<td>584867</td>
<td>0.15</td>
</tr>
<tr>
<td>Paper, etc.</td>
<td>17</td>
<td>28848</td>
<td>0.01</td>
</tr>
<tr>
<td>Wood, etc.</td>
<td>130</td>
<td>38678</td>
<td>0.01</td>
</tr>
<tr>
<td>Construction</td>
<td>6</td>
<td>12791</td>
<td>0.00</td>
</tr>
<tr>
<td>Textiles, etc.</td>
<td>50</td>
<td>77394</td>
<td>0.02</td>
</tr>
<tr>
<td>Non-specified</td>
<td>273</td>
<td>354791</td>
<td>0.09</td>
</tr>
</tbody>
</table>

### Table 2. Energy Consumed by Transport Category and Consumption by Additional Sectors.

<table>
<thead>
<tr>
<th>Sector</th>
<th>(000 TOE)</th>
<th>Footprint Gha</th>
<th>Gha/capita</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transport</td>
<td>4,492</td>
<td>3,603,199</td>
<td>0.906</td>
</tr>
<tr>
<td><strong>of which:</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Air</td>
<td>789</td>
<td>631,601</td>
<td>0.159</td>
</tr>
<tr>
<td>Road</td>
<td>3,659</td>
<td>2,932,670</td>
<td>0.737</td>
</tr>
<tr>
<td>Rail</td>
<td>43</td>
<td>37,427</td>
<td>0.009</td>
</tr>
<tr>
<td>Inland Navigation</td>
<td>2</td>
<td>1,501</td>
<td>0</td>
</tr>
<tr>
<td><strong>Others</strong></td>
<td>4,992</td>
<td>5,688,326</td>
<td>1.43</td>
</tr>
<tr>
<td><strong>of which:</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Agriculture</td>
<td>329</td>
<td>329,669</td>
<td>0.083</td>
</tr>
<tr>
<td>Comm. and Publ.</td>
<td>1,894</td>
<td>2,369,108</td>
<td>0.595</td>
</tr>
<tr>
<td>Residential</td>
<td>2,769</td>
<td>2,989,550</td>
<td>0.751</td>
</tr>
</tbody>
</table>

### Table 3. Summary of Car Transport Footprint including Uplift and Built Land Component.

<table>
<thead>
<tr>
<th>1000 Car km</th>
<th>Emission (gCO2/km)</th>
<th>Uplift %</th>
<th>Tonnes CO2</th>
<th>Gha</th>
<th>Gha/car km</th>
</tr>
</thead>
<tbody>
<tr>
<td>30,894,545</td>
<td>168</td>
<td>51%</td>
<td>7,837,328</td>
<td>2,099,647</td>
<td>0.000068</td>
</tr>
<tr>
<td>Built-land (ha)</td>
<td>44,552</td>
<td></td>
<td>2,13</td>
<td>1,247</td>
<td>0.00006</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td><strong>2,250,447</strong></td>
<td></td>
<td><strong>0.000074</strong></td>
</tr>
</tbody>
</table>

### Table 4. Summary of Bus Footprint including Uplift and Built Land Components.

<table>
<thead>
<tr>
<th>Bus Eireann</th>
<th>Km</th>
<th>Mpg</th>
<th>Litres</th>
<th>Tonnes CO2</th>
<th>Uplift %</th>
<th>Gha/km</th>
<th>Gha/tonne km</th>
</tr>
</thead>
<tbody>
<tr>
<td>Provincial city services</td>
<td>8,198,000</td>
<td>6</td>
<td>3,859,699</td>
<td>10,344</td>
<td>51%</td>
<td>0.0005</td>
<td></td>
</tr>
<tr>
<td>Other services (own)</td>
<td>75,947,000</td>
<td>9.5</td>
<td>22,583,110</td>
<td>60,523</td>
<td>51%</td>
<td>0.0003</td>
<td></td>
</tr>
<tr>
<td>Services sub-contracted</td>
<td>59,876,000</td>
<td>9.5</td>
<td>17,804,341</td>
<td>47,716</td>
<td>51%</td>
<td>0.0003</td>
<td></td>
</tr>
<tr>
<td>Dublin Bus</td>
<td>57,910,000</td>
<td>5.2</td>
<td>31,459,148</td>
<td>84,311</td>
<td>51%</td>
<td>0.0006</td>
<td></td>
</tr>
<tr>
<td><strong>Built-land (ha)</strong></td>
<td>44,552</td>
<td>0.6%</td>
<td>2.13</td>
<td>2.19</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>83,324</strong></td>
<td></td>
<td><strong>0.0004</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Table 5. Summary of Train Footprint including Uplift and Built Land Component.

<table>
<thead>
<tr>
<th>Train km</th>
<th>kg CO2/km</th>
<th>Tonnes CO2</th>
<th>Uplift %</th>
<th>Tonnes CO2</th>
<th>Footprint</th>
<th>Gha/train km</th>
</tr>
</thead>
<tbody>
<tr>
<td>10,275,000</td>
<td>11.66</td>
<td>119,852</td>
<td>57%</td>
<td>1,88,168</td>
<td>50,411</td>
<td>0.0049</td>
</tr>
<tr>
<td>398,309,000</td>
<td>17.3</td>
<td>6,891</td>
<td>57%</td>
<td>10,818</td>
<td>2,898</td>
<td>0.000007</td>
</tr>
<tr>
<td>Length (km)</td>
<td>3,314</td>
<td>1,060</td>
<td>2.13</td>
<td>2.19</td>
<td>4,947</td>
<td>0.00048</td>
</tr>
</tbody>
</table>

### Table 6. Summary of Commercial Transport Footprint including Uplift and Built Land Component.

<table>
<thead>
<tr>
<th>Type</th>
<th>Vehicle km</th>
<th>g CO2/km</th>
<th>Tonnes CO2</th>
<th>Uplift %</th>
<th>Total</th>
<th>Gha</th>
</tr>
</thead>
<tbody>
<tr>
<td>HCV</td>
<td>1,802,000,000</td>
<td>1,045</td>
<td>1,883,090</td>
<td>51%</td>
<td>2,843,466</td>
<td>761,774</td>
</tr>
<tr>
<td>LCV</td>
<td>N/A</td>
<td>N/A</td>
<td>3,670,478</td>
<td>51%</td>
<td>5,542,422</td>
<td>1,484,833</td>
</tr>
<tr>
<td><strong>Built-land (ha)</strong></td>
<td>44,552</td>
<td>9.4%</td>
<td>2.13</td>
<td>2.19</td>
<td>19,535</td>
<td></td>
</tr>
</tbody>
</table>
total value for transport exceeds the footprint of domestic and industrial energy provision. The majority of this is taken up by road transport fuel. The footprint of agriculture is comparatively small, but this finding must be treated with caution as much of the energy used within farms was included in other sections (for example, use of engine fuel was included under transport). For family farms, it was not possible to distinguish between energy used for farm activities and energy used for domestic purposes.

Private car transport comprises a significant fraction of the transport footprint. While each individual car footprint is relatively small, the number of cars is very large (see Table 3). The much smaller contribution by public transport is evident.

Ireland-specific conversion factors were calculated for car, bus, rail and freight journeys together with an estimate for the energy necessary to construct and maintain vehicles and infrastructure (see Tables 4 and 5). The total area of the road network was estimated from primary data. Given that roads normally displace bio-productive land, the footprint estimates how much global crop area is necessary to compensate for losses to built land. It should be noted that the overall bus footprint is higher than those reported for other countries: most Irish buses operate on congested Dublin roads.

The Road Freight Transport Survey 2003 (CSO, 2004a) provided data used in the calculation of the heavy commercial transport footprint (see Table 6). To account for light commercial vehicles, a compound value for the other road transport categories was subtracted from the total road estimate within the Energy Balance. The total commercial transport footprint slightly exceeds the car footprint, making it the single largest transport category; the weight of freight transported by heavy commercial vehicles more than tripled between 1993 and 2004 (CSO, 2004a).
The method for calculating the footprint for Ireland’s crop production was adapted from that used in standardised foot-printing. Global yields and equivalence factors were applied to translate tonnages of produce into global cropland and subsequently into global hectares. Crop production estimates and yield figures were obtained from the CSO Farm Land Utilisation data. Irish-grown cereals and sugar beet contributed most to the footprint (see Table 7). Vegetable crops have larger yields and are produced in larger quantities but have a smaller footprint per tonne. The footprint for imported foodstuffs was calculated using CSO trade data (CSO, 2005) and conversion factors from Barrett et al. (2001). However, the equivalence factors adopted by Barrett et al. were replaced by those provided more recently by Wackernagel & Loh (2004). Table 8 summarises the traded food footprint calculation results.

For grazing animals the footprint (see Table 9) is an estimation of grass consumed by slaughtered livestock within the study year as well as the total amount consumed by live animals throughout the year. Ireland-specific conversion factors were calculated for pig and poultry meat. To avoid double accounting, the footprint of protein oilcakes was not included as this was already incorporated within the imported feed footprint (see Table 8). The footprint of pig and poultry meat is shown in Table 10.

In order to account for traded food, it was necessary to estimate the extent to which both domestically grown and imported cereals and other feedstuffs (such as imported oil crops) were used to satisfy the export market. The same method was applied to domestic livestock and milk production (the latter being represented by live dairy animals). The feed demand of live animals was assumed to be equal to the demand placed by slaughtered animals during the previous years. The overall pasture and arable footprint is shown in Table 11.

### Table 9. Grazing Land Production by Major Livestock Category.

<table>
<thead>
<tr>
<th>Cattle</th>
<th>Pasture (Gha/cap)</th>
<th>Sheep</th>
<th>Pasture (Gha/cap)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Factory Slaughtered</td>
<td>0.147</td>
<td>Live Ewes</td>
<td>0.11</td>
</tr>
<tr>
<td>Abattoir Slaughtered</td>
<td>0.007</td>
<td>Live Lambs</td>
<td>0.014</td>
</tr>
<tr>
<td>On-farm Deaths</td>
<td>0.011</td>
<td>Live Rams</td>
<td>0.0018</td>
</tr>
<tr>
<td>Live Exports</td>
<td>0.01</td>
<td>Exported Live</td>
<td>0.0004</td>
</tr>
<tr>
<td>Live Herd</td>
<td>0.904</td>
<td>Slaughtered Sheep</td>
<td>0.034</td>
</tr>
</tbody>
</table>

### Table 10. Summary of Pig and Poultry Production Footprints.

<table>
<thead>
<tr>
<th>Pig Meat</th>
<th>Tonnes Feed</th>
<th>Wheat (gha)</th>
<th>Barley (gha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slaughtered</td>
<td>214,668</td>
<td>805,005</td>
<td>215,473</td>
</tr>
<tr>
<td>Live Exports</td>
<td>17,875</td>
<td>67,030</td>
<td>13,831</td>
</tr>
<tr>
<td>Total</td>
<td>232,543</td>
<td>872,035</td>
<td>229,304</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Poultry Meat</th>
<th>Tonnes Feed</th>
<th>Wheat (gha)</th>
<th>Barley (gha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slaughtered</td>
<td>175,258</td>
<td>364,914</td>
<td>111,445</td>
</tr>
<tr>
<td>Live</td>
<td>42,450</td>
<td>90,353</td>
<td>9,030</td>
</tr>
<tr>
<td>Live Exports</td>
<td>194</td>
<td>369</td>
<td>118</td>
</tr>
<tr>
<td>Total</td>
<td>217,902</td>
<td>455,636</td>
<td>120,593</td>
</tr>
</tbody>
</table>

### Table 11. Overall Summary of Pasture and Arable Footprint accounting for affects of trade.

<table>
<thead>
<tr>
<th></th>
<th>Import</th>
<th>Produced gha cap</th>
<th>Export</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crop land (gha/cap)</td>
<td>1.16</td>
<td>0.53</td>
<td>0.33</td>
</tr>
<tr>
<td>Pigmeat exports (domestic grain)</td>
<td></td>
<td></td>
<td>0.07</td>
</tr>
<tr>
<td>Live pig exports (domestic grain)</td>
<td></td>
<td></td>
<td>0.01</td>
</tr>
<tr>
<td>Poultry meat exports (domestic grain)</td>
<td></td>
<td></td>
<td>0.03</td>
</tr>
<tr>
<td>Live poultry exports (domestic grain)</td>
<td></td>
<td></td>
<td>0.00005</td>
</tr>
<tr>
<td>Crude inedible materials</td>
<td></td>
<td></td>
<td>0.0019</td>
</tr>
<tr>
<td>Imported feed (mostly oil crops) used on exported animals</td>
<td></td>
<td></td>
<td>0.3</td>
</tr>
<tr>
<td>Concentrate estimates to reflect cereal demand of previous years</td>
<td></td>
<td></td>
<td>0.19</td>
</tr>
<tr>
<td>Pasture (gha/cap)</td>
<td>0.51</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cattle disposals</td>
<td></td>
<td>0.17</td>
<td>0.11</td>
</tr>
<tr>
<td>Live herd</td>
<td></td>
<td>0.9</td>
<td>0.01</td>
</tr>
<tr>
<td>Dairy exports (Adjusted for biocapacity of previous years)</td>
<td></td>
<td></td>
<td>0.22</td>
</tr>
<tr>
<td>Imported feed (animal meal) used on exported animals</td>
<td></td>
<td></td>
<td>0.43</td>
</tr>
<tr>
<td>Live Sheep</td>
<td></td>
<td>0.13</td>
<td>0.0004</td>
</tr>
<tr>
<td>Sheep meat (Adjusted for biocapacity of previous years)</td>
<td></td>
<td>0.03</td>
<td>0.026</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.08</td>
</tr>
</tbody>
</table>

**WASTE**

The footprint for municipal waste estimates waste was calculated in terms of the land required to absorb its embodied carbon. Embodied energy estimates were taken from a number of sources, especially Alcorn (1998) and Buchanan &
### Table 12. Embodied Energy, Associated Carbon and Footprint of Domestic Landfilled Waste.

<table>
<thead>
<tr>
<th>Landfill</th>
<th>Mj/Kg</th>
<th>Tonnes C/tonne</th>
<th>Gha/tonne</th>
<th>Household tonnes</th>
<th>Gha</th>
<th>Gha/cap</th>
</tr>
</thead>
<tbody>
<tr>
<td>Paper</td>
<td>32</td>
<td>0.63</td>
<td>0.61</td>
<td>274,072</td>
<td>168,074</td>
<td>0.0422</td>
</tr>
<tr>
<td>Glass</td>
<td>21</td>
<td>0.41</td>
<td>0.4</td>
<td>54,486</td>
<td>21,928</td>
<td>0.0055</td>
</tr>
<tr>
<td>Plastic</td>
<td>84</td>
<td>1.64</td>
<td>1.61</td>
<td>142,900</td>
<td>230,037</td>
<td>0.0578</td>
</tr>
<tr>
<td>Ferrous</td>
<td>42.5</td>
<td>0.83</td>
<td>0.81</td>
<td>25,906</td>
<td>21,100</td>
<td>0.0053</td>
</tr>
<tr>
<td>Aluminium</td>
<td>193</td>
<td>3.77</td>
<td>3.7</td>
<td>10,884</td>
<td>40,256</td>
<td>0.0101</td>
</tr>
<tr>
<td>Other metals</td>
<td>50</td>
<td>0.98</td>
<td>0.96</td>
<td>8,458</td>
<td>8,104</td>
<td>0.002</td>
</tr>
<tr>
<td>Textiles</td>
<td>95</td>
<td>1.86</td>
<td>1.82</td>
<td>95,973</td>
<td>83,697</td>
<td>0.021</td>
</tr>
<tr>
<td>Organics</td>
<td>10.26</td>
<td>0.2</td>
<td>0.2</td>
<td>395,881</td>
<td>77,839</td>
<td>0.0196</td>
</tr>
<tr>
<td>Wood</td>
<td>12.4</td>
<td>0.24</td>
<td>0.24</td>
<td>272,548</td>
<td>365,617</td>
<td>0.0919</td>
</tr>
<tr>
<td>Others</td>
<td>70</td>
<td>1.37</td>
<td>1.34</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td>1,231,108</td>
<td>1,016,652</td>
<td></td>
<td></td>
<td>0.2555</td>
</tr>
</tbody>
</table>


<table>
<thead>
<tr>
<th>Landfill</th>
<th>Mj/Kg</th>
<th>Tonnes C/tonne</th>
<th>Gha/tonne</th>
<th>Commercial tonnes</th>
<th>Gha</th>
<th>Gha/cap</th>
</tr>
</thead>
<tbody>
<tr>
<td>Paper</td>
<td>32</td>
<td>0.63</td>
<td>0.61</td>
<td>292,289</td>
<td>179,245</td>
<td>0.045</td>
</tr>
<tr>
<td>Glass</td>
<td>21</td>
<td>0.41</td>
<td>0.4</td>
<td>43,180</td>
<td>17,378</td>
<td>0.0044</td>
</tr>
<tr>
<td>Plastic</td>
<td>84</td>
<td>1.64</td>
<td>1.61</td>
<td>61,830</td>
<td>99,532</td>
<td>0.025</td>
</tr>
<tr>
<td>Ferrous</td>
<td>42.5</td>
<td>0.83</td>
<td>0.81</td>
<td>9,847</td>
<td>8,020</td>
<td>0.002</td>
</tr>
<tr>
<td>Aluminium</td>
<td>193</td>
<td>3.77</td>
<td>3.7</td>
<td>5,366</td>
<td>19,847</td>
<td>0.005</td>
</tr>
<tr>
<td>Other metals</td>
<td>50</td>
<td>0.98</td>
<td>0.96</td>
<td>701</td>
<td>672</td>
<td>0.0002</td>
</tr>
<tr>
<td>Textiles</td>
<td>95</td>
<td>1.86</td>
<td>1.82</td>
<td>7,594</td>
<td>13,825</td>
<td>0.0035</td>
</tr>
<tr>
<td>Organics</td>
<td>10.26</td>
<td>0.2</td>
<td>0.2</td>
<td>123,709</td>
<td>24,324</td>
<td>0.0061</td>
</tr>
<tr>
<td>Wood</td>
<td>12.4</td>
<td>0.24</td>
<td>0.24</td>
<td>6,015</td>
<td>1,429</td>
<td>0.0004</td>
</tr>
<tr>
<td>Others</td>
<td>70</td>
<td>1.37</td>
<td>1.34</td>
<td>50,985</td>
<td>68,395</td>
<td>0.0172</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td>601,516</td>
<td>432,668</td>
<td></td>
<td></td>
<td>0.1087</td>
</tr>
</tbody>
</table>


<table>
<thead>
<tr>
<th>Recycled</th>
<th>Mj/Kg</th>
<th>Tonnes C/tonne</th>
<th>Gha/tonne</th>
<th>Household tonnes</th>
<th>Gha</th>
<th>Gha/cap</th>
</tr>
</thead>
<tbody>
<tr>
<td>Paper</td>
<td>21</td>
<td>0.41</td>
<td>0.4</td>
<td>75,723</td>
<td>30,474</td>
<td>0.0077</td>
</tr>
<tr>
<td>Glass</td>
<td>5</td>
<td>0.1</td>
<td>0.1</td>
<td>52,347</td>
<td>5,016</td>
<td>0.0013</td>
</tr>
<tr>
<td>Plastic</td>
<td>27</td>
<td>0.53</td>
<td>0.52</td>
<td>9,618</td>
<td>4,977</td>
<td>0.0013</td>
</tr>
<tr>
<td>Ferrous</td>
<td>10</td>
<td>0.2</td>
<td>0.19</td>
<td>2,182</td>
<td>962</td>
<td>0.0002</td>
</tr>
<tr>
<td>Aluminium</td>
<td>23</td>
<td>0.45</td>
<td>0.44</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Other metals</td>
<td>19</td>
<td>0.37</td>
<td>0.36</td>
<td>2,837</td>
<td>761</td>
<td>0.0002</td>
</tr>
<tr>
<td>Textiles</td>
<td>14</td>
<td>0.27</td>
<td>0.27</td>
<td>7,503</td>
<td>244</td>
<td>0.0001</td>
</tr>
<tr>
<td>Organics</td>
<td>0.703</td>
<td>0.01</td>
<td>0.01</td>
<td>32,917</td>
<td>443</td>
<td>0.0001</td>
</tr>
<tr>
<td>Wood</td>
<td>1.7</td>
<td>0.03</td>
<td>0.03</td>
<td>2,625</td>
<td>704</td>
<td>0.0002</td>
</tr>
<tr>
<td>Others</td>
<td>14</td>
<td>0.27</td>
<td>0.27</td>
<td></td>
<td></td>
<td>0</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td>185,752</td>
<td>43,582</td>
<td></td>
<td></td>
<td>0.011</td>
</tr>
</tbody>
</table>

### Table 15. Embodied Energy, Associated Carbon and Footprint of Commercial Recycled Waste.

<table>
<thead>
<tr>
<th>Recycled</th>
<th>Mj/Kg</th>
<th>Tonnes C/tonne</th>
<th>Gha/tonne</th>
<th>Commercial tonnes</th>
<th>Gha</th>
<th>Gha/cap</th>
</tr>
</thead>
<tbody>
<tr>
<td>Paper</td>
<td>21</td>
<td>0.41</td>
<td>0.4</td>
<td>283,154</td>
<td>113,953</td>
<td>0.0286</td>
</tr>
<tr>
<td>Glass</td>
<td>5</td>
<td>0.1</td>
<td>0.1</td>
<td>20,740</td>
<td>1,987</td>
<td>0.0005</td>
</tr>
<tr>
<td>Plastic</td>
<td>27</td>
<td>0.53</td>
<td>0.52</td>
<td>38,540</td>
<td>19,942</td>
<td>0.005</td>
</tr>
<tr>
<td>Ferrous</td>
<td>10</td>
<td>0.2</td>
<td>0.19</td>
<td>9,558</td>
<td>1,832</td>
<td>0.0005</td>
</tr>
<tr>
<td>Aluminium</td>
<td>23</td>
<td>0.45</td>
<td>0.44</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Other metals</td>
<td>19</td>
<td>0.37</td>
<td>0.36</td>
<td>1,046</td>
<td>381</td>
<td>0.0001</td>
</tr>
<tr>
<td>Textiles</td>
<td>14</td>
<td>0.27</td>
<td>0.27</td>
<td>626</td>
<td>168</td>
<td>0</td>
</tr>
<tr>
<td>Organics</td>
<td>0.703</td>
<td>0.01</td>
<td>0.01</td>
<td>14,391</td>
<td>194</td>
<td>0</td>
</tr>
<tr>
<td>Wood</td>
<td>1.7</td>
<td>0.03</td>
<td>0.03</td>
<td>120,793</td>
<td>3,935</td>
<td>0.001</td>
</tr>
<tr>
<td>Others*</td>
<td>14</td>
<td>0.27</td>
<td>0.27</td>
<td>52,162</td>
<td>13,995</td>
<td>0.0035</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td>541,010</td>
<td>156,387</td>
<td></td>
<td></td>
<td>0.0393</td>
</tr>
</tbody>
</table>
Table 16. Overall Summary of Footprint Categories.

<table>
<thead>
<tr>
<th>Footprint Category</th>
<th>Calculated Footprint</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(Global hectares)</td>
</tr>
<tr>
<td>Energy</td>
<td>12,471,126</td>
</tr>
<tr>
<td>Crop</td>
<td>2,972,360</td>
</tr>
<tr>
<td>Pasture</td>
<td>3,246,130</td>
</tr>
<tr>
<td>Forest</td>
<td>1,994,610</td>
</tr>
<tr>
<td>Built</td>
<td>782,200</td>
</tr>
<tr>
<td>Fishing</td>
<td>1,528,349</td>
</tr>
<tr>
<td>Total</td>
<td>22,994,775</td>
</tr>
</tbody>
</table>

Honey (1994). The footprint has been calculated for both domestic and commercial waste sent to landfill (see Tables 12 and 13 respectively) and domestic and commercial recycled waste (see Tables 14 to 15 respectively).

As can be seen from Tables 12 to 15, paper and organic waste form a significant proportion of the overall footprint. The ‘other’ waste category refers to such categories as waste oils, tyres and electronic equipment.

Based on information obtained from local authorities and some of the larger waste collection companies, it was estimated that transport of a tonne of urban-generated waste to landfill or recycling plant requires 3 l of fuel, and the comparable value for rural generated waste is 15 l.

The larger footprint described here for the footprint of pastureland use represents the greatest departure from standardised footprinting method. By calculating the feed required by both slaughtered and live animals within the study year, the footprint described here incorporates the indirect demand placed on a pasture area.

The transport footprint reflects the high level of car dependency in Ireland. In addition, the low car occupancy rate (1.4 persons per car, based on a value provided by the Public Transport User Association in Victoria as being more efficient than bus transport. Effective car-pooling has been championed by such organisations as the Public Transport User Association in Victoria as being more efficient than bus transport. While full car occupancy is impractical, doubling car occupancy would significantly reduce transport emissions.

The most apparent characteristic of the waste data is the low recycling rates for certain materials. For example, EPA (2004) demonstrates domestic recovery rates of 22% and 49% for paper and glass respectively. This is contrasted by recycling rates of 17% and 6% for aluminium and plastic. The large component of paper within the waste stream has been partially blamed on the growth of computer use, for aluminium and plastic. The large component of paper within the waste stream has been partially blamed on the growth of computer use, for aluminium and plastic. The large component of paper within the waste stream has been partially blamed on the growth of computer use, for the large component of paper within the waste stream has been partially blamed on the growth of computer use, for e-mail and printing increased paper usage by 40%. Increasing urban-generated rural housing increases the amount of fuel (and associated footprint) needed to transport waste.

The method adopted in calculating the water footprint results in an additional footprint of 0.002 and 0.01 gha per tonne respectively.

WATER

An average annual surplus water estimate for Ireland (representing average rainfall minus evapotranspiration) of 479mm translated into a conversion factor of 4.790m³/ha. The Quality of Drinking Water in Ireland 2003 (EPA, 2004a) estimated that 1,700,000m³ of water per day were treated by the public sanitary authorities and group water schemes. The overall water footprint was calculated to be 0.04 ha per capita. The water footprint is included here as it may be of policy relevance. It was assumed that all land used in collecting water is also used for some other purpose, especially agriculture. Therefore the water footprint was not aggregated with other component footprints in calculating the overall footprint.

OVERALL FOOTPRINT

Results for each component and for the total footprint are provided in Table 16. Energy and pastureland components contribute most to the overall footprint. This reflects Irish conditions, namely high dependence on imported hydrocarbon fuels and agriculture focused on pasture-based meat production.

DISCUSSION

While use of coal is slowly reducing and gas may take its place, the growth in oil dependency is unlikely to be abated in the short to medium term, particularly as the demand for transport fuel continues to rise sharply. This use of imported oil raises an interesting methodological point. If the energy needed to extract and refine the oil consumed is included, the oil footprint would increase by approximately 33% (Moffet & Miller, 1993). Furthermore, the method adopted here follows standard practice in that the embodied energy in exported goods is not included in the overall footprint. Thus, if a resource-rich nation produces all its energy and goods within its borders and achieves a high level of export of its production, then the footprint calculated suggests that little energy is consumed. In addition, it could be debated that following the standard method (whereby new forest area is adopted as the metric for energy consumption) is inadequate, since it fails to take account of other biotypes, and that forests emit considerable amounts of methane (Keppler et al., 2006), or indeed that forest products will eventually decay to carbon dioxide.

In relation to agriculture, a field of crop will have no inherent environmental impact, but the application of fertilizers, and the use of transport fuel, will have an impact both environmentally and in terms of footprint calculation. Coulter et al. (2004), for example, demonstrate the large quantities of mineral fertilizers, with associated high embodied energy values, that are necessary to satisfy the intensive cattle sector. It is important to consider footprint calculation results in the context of the methodology applied. The method of calculation adopted here for the footprint of pastureland use represents the greatest departure from standardised footprinting method. By calculating the feed required by both slaughtered and live animals within the study year, the footprint described here incorporates the indirect demand placed on a pasture area.

The method adopted in calculating the water footprint results in an additional footprint of 0.002 and 0.01 gha per tonne respectively.

CONCLUSIONS

Ecological footprinting has become a very useful and adaptable policy-relevant tool. This is clear from the fact that no other aggregate indicator of sustainability has attracted such recognition and support.
from decision-makers. However, it has the weakness of being primarily a measure of resource use intensity, and does not claim to include the social and economic pillars of sustainability. It is therefore not adequate as the sole indicator for sustainability. Standardised footprinting has the advantage of allowing comparisons between countries, but using a common method for all countries may fail to account for country-specific conditions, making interpretation of results problematic. Increased region-specific relevance may be achieved through the selection of ‘bottom-up’ data sources and tailored conversion factors. The resultant footprint may differ from that calculated using the standardised method, but may provide more valuable information for national and regional scale decision-making. More work is needed to ensure that specific regional and national conditions are incorporated into calculations, so that, where possible, the resulting footprint is more concrete and less notional, and is therefore of greater value to stakeholders and decision-makers.

REFERENCES

INTRODUCTION

After the establishment of the United Nations Framework Convention on Climate Change (UNFCCC) in 1992 and five years of negotiating and considering different implementation scenarios, more than 160 nations met in Kyoto in December 1997 to negotiate a bilateral protocol with binding limitations on greenhouse gases (GHGs) for the industrialised nations. Russia’s ratification of the Kyoto Protocol in November 2004 marked the last juristically important step on the road to implementation, and the protocol became legally binding on 16th February 2005. A set of flexible mechanisms are included within the protocol to enable flexibility for industrialised countries to fulfill their quantitative emission reduction targets abroad.

The main reason for the incorporation of these flexible mechanisms, such as the project-based Clean Development Mechanism (CDM), is based on the assumption that a GHG abatement scheme with geographical flexibility achieves the same environmental benefits at lower costs than a scheme without flexibility. This assumption is valid if CO₂ and other GHGs mix rapidly in the atmosphere and GHG concentration is approximately equal all over the globe. Therefore, it does not make a substantial difference to the climatic system where from the GHG emissions are released or reduced from an environmental perspective. However, the marginal cost of abatement for GHG emission reductions varies considerably from country to country, especially from industrialised to developing countries. Hence, it is cost-efficient on a global scale to reduce the GHG emission in countries with lower abatement costs.

Thus, the project-based flexible mechanism of CDM allows industrialised countries (to some extent) to meet their obligations and reduction commitments in a cost-effective manner by generating GHG emission reduction credits in developing countries. At the same time, developing countries (countries without emission reduction commitments under the Kyoto regime) should benefit through the transfer of cleaner technologies and financial resources for specific development projects, which are contributing to the objectives of the UNFCCC. Therefore, CDM reflects a twin approach, as outlined in Article 12.2 of the Kyoto Protocol:

“The purpose of the clean development mechanism shall be to assist Parties not included in Annex I in achieving sustainable development and in contributing to the ultimate objective of the Convention, and to assist Parties included in Annex I in achieving compliance with their quantified emission limitation and reduction commitments under Article 3.”

Hence, it is assumed that CDM implies direct and indirect benefits for developing countries, which are related to sustainable development components, e.g. local/regional environmental benefits, infrastructure development, technology transfer, additional generation of employment, etc (Shresta & Timilsina, 2002).

Analogous to the Rio Declaration on Environment and Development adopted at the United Nations Conference on Environment and Development (UNCED) held in Rio de Janeiro in June 1992, the protocol does not specify either how this important objective would be achieved or what sustainability criteria have to be applied. The definition of the sustainability criteria (sets) as well as methods to assess their fulfilment has to be defined by the host country of a particular CDM project on a national level according to their national development plans and policies.

This task tends to be difficult as sustainable development is still much more a vague concept than a well-defined term. There is no globally accepted definition of sustainability. Neither are globally accepted tools available which can help to measure the assumed direct and indirect benefits and compare the impacts of different CDM project alternatives on the local/regional sustainable development process. Despite the sustainability criteria, CDM projects have to fulfil the criteria of additivity. While the allowances of the Joint Implementation and the Emission Trading are transferred among Annex I country accounts, the allowances generated in CDM projects are additional to the assigned amounts and increase the total volume of available allowances. To avoid host countries and investors overstating the emission reduction of CDM projects, the additivity criterion has been introduced.

CDM projects are also additional in a technical sense (“environmental additivity”) if GHG emission abatements are achieved, which are:

“...additional to any that would occur in the absence of such activities” (UNFCCC 1998, paragraph 5c, Article 12).

Environmentalists argued at the very beginning that the developing countries might have the incentive to bypass the sustainability criteria by outlining negligible minimum criteria in order to attract as much CDM projects as possible. In real life it can be observed that the sustainability issue seems to play almost no role at all. In most of the Project Design Documents (PDD) the sustainability issue is reduced to the environmental additivity aspect reflecting that CDM projects are intrinsically sustainable if the sustainability definition is narrowed towards environmental aspects only.
The aim of those two criteria is to distinguish CDM projects from ‘business as usual’ (BAU) projects, which are already economically attractive. The practical application provokes different interpretations and became one of the most difficult issues for the practical implementation of the CDM in the past (Meyers, 1999; Chomitz, 1999; Grubb et al., 1999).

Whereas the additionality criteria assesses quantitatively a future emission threshold level and tries to prove that this development is caused by the CDM, the sustainability criteria have to assess this future development process qualitatively and try to verify whether the forecasted scenario will be more “sustainable” than the current status quo. Thus, both criteria compare a current status quo (reference case) with a forecasted scenario.

The construction of the reference case, also known as the baseline scenario, the prediction of future emission scenarios and the comparison of these forecasts with the vision of sustainable development are still the crucial points in evaluating potential GHG abatement projects and have been controversially discussed in the literature (Chomitz, 2002; Shrestha & Timilsina, 2002; Springer, 2003; Michaelowa & Jotzko, 2005; Shrestha & Shrestha, 2004; Illum & Meyer, 2004).

While in recent years the Methodology Panel of the CDM Executive Board has made major efforts to clarify the additionality issue, the vague concept of sustainability is still not broken down into measurable and comparable indicators and criteria, which allow the comparison of CDM project impacts on regional sustainable development.

The different steps of the consolidated additionality assessment tool are analysed to examine the hypothesis that the two criteria applications follow one ratio and thus, one integrative assessment method would be sufficient to prove that a potential GHG abatement project is additional and supporting a regional sustainability path. It is assumed that analysing the different levels of additionality (financial, technical and social) implicitly allows inferences on the project impacts on a regional development process. Thus, the central research question is:

**What amendments and complements of the consolidated additionality assessment tool are needed to decide whether a project is supporting a regional sustainability process or not?**

This paper (and the underlying thesis) analyses for the first time the question whether the initial idea of the additionality and sustainability principle needs two collateral concepts or, if the similarities of both principles are sufficient, that one integrative assessment method covering both criteria would be enough.

After the introduction of the sustainability issue, the consolidated additionality assessment tool will be analysed, and then the cross-cutting elements of both criteria will be outlined. The conclusion highlights the first results and provides an overview of the further steps to completion of the research.

**THE SUSTAINABILITY PRINCIPLE**

The flexible Kyoto mechanisms are designed to support the achievement of the agreed GHG reduction commitments of industrialised nations and to support sustainable development in developing countries. Problems arise if the prediction of the baseline (forecast of emissions) are inflationary in order to achieve saleable allowances, which are not underpinned with real emission reductions. This currently applies to countries in transition (creation of “hot air”) and could apply to developing countries in the future (“tropical air”). It can be observed that donating and investing organisations may have a vested interest in choosing baselines that inflate estimates of the reduction achieved. This situation can be problematic for host countries, which may not have the capacity to assess whether or not gaming is taking place. Opponents of CDM may also argue that the host countries with no obligations (at present) under the Kyoto protocol have little incentive to proof the estimated baseline in detail (Parkinson et al., 2001; Gupta et al., 2003).

Due to lack of agreement on the meaning of the term ‘sustainable development,’ and partly because the UNFCCC may not want the CDM to appear to be dictating to non-Annex I Parties the development path they should follow, there is no globally accepted minimum standard or assessment criteria for the SD issue up to now (Foot, 2004). Advocates of a global minimum SD standard argue that host countries may compete with each other, approving as many projects as possible in order to attract further investment and alleviate local poverty (Michaelowa, 1998; Salter, 2003). This would clearly affect the integrity of the CDM’s goal of delivering sustainable projects (Foot, 2004) and could lead to an increase of GHG emissions by inflationary baseline settings.
Recently, a series of attempts to measure SD impacts of CDM projects has been undertaken. The international NGOs, such as the Worldwide Fund for Nature (WWF) and the SouthSouthNorth (SSN), took the pioneering role in outlining standard procedures for SD appraisals. The WWF has developed the ‘Gold Standard’ procedure, a set of quality measures that provides an independent benchmark for CDM projects with regard to the SD impacts (Salter, 2003). The SSN established a widely recognised Sustainable Development Tool, which consists of eligibility screens, additionality filters and sustainable development indicators (Thorne et al., 2001). The German Institute for Energy Economics and the Rational Use of Energy (IER) described a set of ranking methods to assess the contribution of CDM projects to Sustainable Development (Thomas et al., 2001). A South African research group has proposed a set of sustainability criteria to be applied to CDM projects (Spalding-Fetcher et al., 2002). In South Africa, the government has proposed a list of sustainability guidelines (Directorate of Global Climate Change and Ozone Layer Protection, 2002) and the National Strategy Study in Indonesia presents a list of sustainability criteria (State Ministry for Environment, 2001).

Besides the attempts of the host countries and NGOs, most of the "governmental" carbon funds do encompass a SD appraisal in their terms of references, where they oblige the project developers to provide information on the project impacts with regard to SD.

However, an assessment of the Project Design Documents, which are published under the UNFCCC website, convey the impression that project developers tend to narrow the sustainability aspects down to environmental aspects only. For example, for most of the landfill gas projects, the issue of reducing global warming potential by transforming methane into carbon dioxide seems to be sufficient to define a sustainable project.

Based on Sutter (2003), the design of the several approaches and methods to conduct sustainability assessments of CDM projects can be divided into four different categories (see Table 1).

Although the development of SD criteria on a host nation level is inflationary, it is unlikely that a global minimum standard or approach will be available in the near future. In negotiation processes between investors and approving authorities, the project impacts on SD still are negligible while the additionality issue plays the major role.

Hence, the crucial issue of avoiding an abuse of the CDM due to the creation of ‘hot air’ remains unresolved. Among others, the WWF is arguing that the Conference of the Members of the Parties (COP/MOP) must give the CDM Executive Board the mandate to develop a mandatory proposal on how the SD objectives of the CDM can be strengthened.

Additionality is one of the complex issues of CDM modalities and procedures and has been interpreted in many different ways. Although the definition of additionality laid down in the Marrakesh Accords is rather vague, the CDM EB has adopted a relatively strict approach with its multi-step consolidated additionality assessment tool. Based on the clarification of the CDM EB, there are two elements of additionality that should be satisfied by a CDM project:

(i) The project emissions (sequestrations) are less than the baseline emissions (sequestrations)
(ii) The proposed project should not be a baseline option

The consolidated additionality assessment tool is providing guidance on assessing the additionality component mentioned in (ii) above. The underlying philosophy of this tool is that a proposed CDM activity is a baseline scenario unless otherwise proven.

Although the CDM EB has clearly stated that the tool is not mandatory and project proponents can develop their own methodology, the assessment tool has stipulated a controversial debate on the COP11/MOP1 in Montreal (Sterk & Wittneben, 2005). While business representatives argue that this approach is far away from business realities and provides additional burdens for project developers (IEAT, 2004), environmental organisations controversially argue that a strict definition of additionality is essential to ensure that the CDM is leading to an additional GHG abatement and minimising free riders (WWF, 2005).

The definition of the baseline, which is the preliminary step to

Table 1. Overview of different approaches to assure SD in CDM projects.

<table>
<thead>
<tr>
<th>Approach</th>
<th>Brief description</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Guidelines</td>
<td>Guidelines define descriptively the aspects of SD and how projects should contribute to this aim. They are often defined in a general and normative manner by the national authority i.e. DNA or international Non-Governmental Organisations. Guidelines are using a holistically descriptive manner rather than clear and applicable procedures or methods.</td>
<td>Indian or Chinese CDM guidelines (issued by the DNA of India and China)</td>
</tr>
<tr>
<td>Checklists</td>
<td>Checklists are a more reductive approach and address selected key issues in a filter-like manner. Checklists consist of clearly defined questions with a closed set of predefined answers. Checklists are at present predominantly used by carbon funds.</td>
<td>CERUPT, KFW Climate Fund, etc.</td>
</tr>
<tr>
<td>Negotiated Targets</td>
<td>Concrete targets are negotiated among stakeholders and project owners in order to assure a measurable contribution to SD. Indicators are defined to measure the achievement of the targets. The solely negotiated process has a wide public participation. It is important to notice that the target does not have to be linked with the project activity directly.</td>
<td>Prototypecarbonfund (PCF)</td>
</tr>
<tr>
<td>Multi-Criteria Methodologies</td>
<td>Multi-Criteria Methodologies define various criteria for several aspects of sustainability and assess project impacts with respect to each criterion.</td>
<td>MATA-CDM, WWF</td>
</tr>
</tbody>
</table>
testify the first condition (i), is among the most crucial issues within the CDM modalities and procedures. For the question of whether two independent approval schemes for the additionality and sustainability issues are needed, the debate around the baseline issue is factored out by using the following assumption:

If a CDM project achieves additional GHG emission abatement to any that would occur in the absence of such activities, the project is

(a) additional in a technical sense ("environmental additionality"); and
(b) contributing to a sustainable development process with regard to the environmental sustainability aspects.

The further analysis of the consolidated additionality assessment tool with regard to the potential to incorporate a sustainability check will be more concentrated on the social, institutional and socio-economic sustainability aspects. The step-wise approach of the consolidated additionality assessment as outlined in Annex 3 of the 15th Report of the Executive Board is visualised in Figure 2 (UNFCCC, 2004).

The analysis will start with Step 1 because Step 0 had to be undertaken in the past, for projects which registered before 31st of December 2005. Here, the projects had to prove that the incentive provided by CDM was seriously considered in the decision to proceed with the project. This evidence had to be based on clear documentation that the CDM incentive had played a major role at or before the time of decision-making. For projects which registered from the 1st of January 2006 onwards this step is outdated.

In Step 1, the alternatives to the project activities, which are consistent with current laws and regulations, have to be identified. Here all other plausible and creditable alternatives to the project activity have to be described that deliver outputs and services with comparable quality, properties and applications. The alternative(s) shall be in compliance with all applicable legal and regulatory requirements.

If the proposed project activity is the only alternative that is in compliance with all regulations, then the proposed project is not additional. In reverse, there is currently no need for projects to over-fulfil the legal requirements.

With regard to institutional sustainability, those projects which are beyond the legal requirements and stipulate the introduction of new policies, regulations or threshold levels could be considered as having a positive impact on the institutional sustainability process. Thus, if Step 1 could be combined with a leverage indicator of legal compliance, a qualitative statement could derive whether the indicated project is supporting the sustainability development path on an institutional/legal level.

If the project does successfully pass Step 1, the next step (Step 2) would be to conduct an investment analysis. Within this step it has to be determined that the proposed activity is less financially attractive without the revenues of CERs than other alternatives. Economically, projects are additional if the sales revenue of the gained CERs has a major influence on the project’s financial feasibility and no Official Development Assistance (ODA) is used. Projects, which are profitable without the CERs sales revenue, are considered as “business as usual” projects and it is expected that these projects will be implemented anyway. To demonstrate the economic additionality, financial indicators such as internal rate of return (IRR), net project value (NPV), cost-benefit-ratio, etc, for the GHG abatement project have to be assessed with and without sales revenue from emission trading.

Figure 2. Consolidated additionality assessment tool.
If the project is financially the most attractive option, then it has to be proven that other barriers (Step 3 - barrier analysis, and Step 4 - common practice analysis) exist which prevent the baseline scenario from occurring (UNFCCC, 2004).

Within Step 2, the socio-economic impacts of the project on a regional scale are not usually considered. In order to allow interpretations as to whether a project does have positive socio-economic impact on the region (e.g. higher regional tax income, job creation, etc) Step 2 has to be enlarged to include a financial flow assessment within the project boundary. The aim is to assess whether a CDM project is leading to regional added value and creating positive impacts on a regional economic development process. In a financial feasibility study, all relevant monetary income and expenditures are included. For the determination of the regional added value, all such income has to be accounted that leads to an increase of the regional factor income, along with the direct income of the region, such as taxes or service fees. For example, a proposed biomass power generation plant will generate energy (heat and electricity) using wood chip residues. The wood chip residues will be locally produced and substitute for hard coal, which is imported from outside of the region. The power plant will create five new jobs. The new proposed biomass power generating plant is thus supporting the regional economy by buying its input material locally and creating additional jobs. If the direct payments toward the regional administration (in terms of tax or direct service fee) remains at least the same, then the new project activity could be claimed to support the socio-economic development of the region. If this is coupled with a decrease of GHG emissions, such socio-economic growth could be considered as being sustainable.

Step 3, barrier analysis, is used to determine whether a proposed project faces barriers that (UNFCCC, 2004):

(a) prevent the implementation of this type of project activity;
and
(b) do not prevent the implementation of at least one of the alternatives.

First, it has to be proven that there are barriers that would prevent the implementation of the proposed project activities. Such barriers could be:

(a) technological barriers;
(a) investment barriers (and risk perception);
(a) barriers due to prevailing practice.

The “classical” technological barriers are the lack of infrastructure to support the implementation of the project, e.g. spare parts for the technology are not available, or that skilled and/or properly trained people are not available to operate and maintain the technology and no education or training institution is providing these skills. If a project proponent wants to overcome these technological barriers, a (institutional) capacity building development is necessary. The combined technology and knowledge transfer is ideally fulfilling the SD philosophy of CDM.

The investment barrier is interconnected with the risk perception of donors and financing institutions and it centres around the question of whether the real or perceived risks associated with the technology or the process of the host country are too high to attract investment for the particular project activity. In reverse, this means whether there is any funding available for this innovative project. In this regard it will become essential to delineate the risks associated with the technology itself and the risk of the host country, e.g. political risk, currency risk, etc. If the risk of the technology is too high due to the degree of innovation, and CDM would provide an incentive to donors and financing institutions to provide financial resources for the project implementation, then CDM would provide a significant positive impact enhancing technology transfer and for the establishment of new innovative technologies associated with higher efficiency or higher environmental standards in the host countries. If these technologies could prove that they are working in this particular environment (of the host countries) it might be easier to attract follow-up investments of the same technology type and therefore enhance the access of host countries to innovative environmental technologies which could support them on their sustainable development path.

Being the “first of a kind” is also a barrier due to prevailing practice where the project developer or approval authorities (or financing institutions) are lacking in familiarity with the technology and are reluctant to use it. This lack of experience and the reluctance to introduce such new technological (and managerial) approaches, as well as the lack of financing resources, are among the main obstacles to the introduction of new innovative technologies in the host countries.

The project would be additional if it could be proven that these barriers are not affecting, or at least affecting less strongly, the other project alternatives.

Step 4 is the analysis of the “Common Practice.” Here, the extent of diffusion of the proposed CDM project type (e.g. technology or practice) in the relevant sector or region is investigated. The aim of this step is to analyse whether the project type is already diffusing in the host country and if there are similar technologies on a similar scale which are implemented in a comparable environment with respect to regulatory framework, investment climate, access to technology, etc (UNFCCC, 2004). If similar projects with no essential differences exist, then the proposed project is not additional unless it can be proven that special policies or development grants support the other similar projects.

Step 5 is the analysis of the “CDM Registration Impacts.” The analysis has to testify that the CDM registration is essential to overcome economic and financial burdens (as identified in Step 2) or other barriers (as identified in Step 3). Among others, the benefits and incentives provided by the registration could be:

(a) financial benefits obtained by the selling of CERs;
(b) attraction of new stakeholders who have access to financial resources or technologies and could help to overcome the barriers (Steps 2/3).

The reviews of the consolidated additionality assessment tool as published on the UNFCCC website indicates that the overall opinion seems to be that Step 5 is redundant and leads to complex approval procedure and higher transaction costs.

CONCLUSION AND PERSPECTIVE

Setting up a second test scheme for SD will overwhelm the CDM process with organisational problems and hinder further progress of this flexible mechanism. It would be more practical if the SD issue could be incorporated into the additionality test scheme because both criteria are following the same guiding principle if it is assumed that SD is defined as a process where one pillar (here the environmental pillar) is improved without worsening the others. Thus, the attainment of environmental additionality will support the SD process within the host region (ensuring that CDM projects are leading to additional GHG abatement, which would have happened in their absence.
The interconnection between the different steps of the consolidated additionality assessment tool and the environmental, social, socioeconomic and institutional aspects of a regional sustainable development process has been examined briefly. Within the underlying thesis, the author is developing a comprehensive and integrated assessment tool encompassing both criteria. The novelty is the combination of qualitative and quantitative elements towards one holistic assessment tool incorporating the consolidated additionality assessment tool, which could be defined as a mixture between checklist and guideline, with sustainability indicators. Based on the toolkit of Material Flow Management (here the emphasis will be placed on Material Flow Analysis), an assessment tool will be developed and tested in two case studies in the field of biomass utilisation in Chile and China. The lessons learned in these case studies will be used to modify the assessment tool, if necessary, and identify policy implications for the introduction or further application to other project types.

The proposed tool will provide a positive impact on the strengthening and simplification of the CDM procedures and modalities and support further development of this flexible mechanism.

REFERENCES


Gupta, J., Olshtoorn, X. 2003. The role of scientific uncertainty in compliance with the Kyoto Protocol to the Climate Change Convention, Environmental Science & Policy 6, 475-486.


Thorne, S. and Raubenheimer, S. 2001, Sustainable Development (SD) appraisal of Clean Development Mechanism (CDM) projects: experiences from the SouthSouthNorth (SSN) project.


CHARACTERISATION OF PYRITIC LEAD-ZINC TAILINGS AT SILVERMINES, CO TIPPERARY

Siobhan N. Jordan and George J. Mullen

ABSTRACT

Vegetation cover represents the most feasible and enduring approach in the stabilisation of metalliferous tailings from Gortmore tailings management facility (TMF) metalliferous mine wastes, through the reduction of air, water, vegetation and soil contamination. However, successful remediation schemes are often hindered by the constrained properties of mine tailings and, in lieu of this fact, this study focused on the general characterisation of the TMF, Silvermines, Co Tipperary. The tailings were collected from the unvegetated surface (20-30cm) of the partially vegetated facility where over nine million tonnes of pyritic metalliferous tailings are deposited in an unlined land impoundment. The tailings were dominated by dolomite (38.6%) and pyrite (32.8%) with smaller quantities of clays, quartz, calcite, barite and bassanite also present. Of the physical and chemical parameters analysed, most were adverse for sustainable plant growth. Overall, the elevated pyrite and metal content and the poor structural and nutrient status of the tailings individually and collectively pose a great challenge in the development of a sustainable reclamation scheme.

INTRODUCTION

The Silvermines district is located on the northern flank of Slieve Phelim-Keeper Hill (N52°4'36", W8°19") and has a long and extensive history of mining, with the earliest records of argentiferous galena mining dating back to the 9th century (Andrew, 1986). This area comprises Lower Carboniferous limestones faulted against Silurian Slates and Devonian Old Red Sandstones (Andrew, 1986). This long history of mining has left permanent scars on the landscape, in particular at the Shallee mines and the TMF in Gortmore. The TMF consists of nine million tonnes of partially vegetated lead and zinc tailings, which occurs over an area of 76.2 hectares (DAFRD, 2000). Concerns about the exposed areas and the increasing vegetation dieback on the tailings pond have amplified recently (DAFRD, 2000) because of fears of a recurrence of the lethal dust blows experienced in 1985. The objective of this study was to characterise the main physical and chemical constraints of the tailings as a preliminary step prior to investigations into possible sustainable vegetative stabilisation of the impoundment.

MATERIALS AND METHODS

Tailings were collected from a depth of 20-30cm at selected unvegetated areas (n=5) in the TMF using a cylindrical soil corer in May 2004. The tailings material was subsequently air-dried and sieved through a 2mm aperture sieve. Additionally, undisturbed clod samples, approximately 250 cm³ in volume, were removed from the tailings surface and the bulk density determined (Blake, 1965). The pyritic content was determined using X-ray powder diffraction using cobalt Kα radiation, while the total and exchangeable metal fractions were extracted as per McCarthy (2002) and Simard (1993), respectively, and analysed using atomic absorption spectrophotometry (AAS). The certified reference material digest (GEW 07604) was routinely analysed to validate accuracy on the AAS. The organic matter content was determined using the loss on ignition procedure (Rowell, 1994); particle density using the Blake & Hartage (1986) methodology and, finally, total porosity was calculated as per Danielson & Sutherland (1986). All parameters were determined in duplicate.

RESULTS AND DISCUSSION

CHEMICAL PROPERTIES

The tailings are dominated by dolomite (38.6%) and pyrite (32.8%), with smaller quantities of clays, quartz, calcite, barite and bassanite also present, as shown in Table 1. The presence of pyrite is problematic under oxidising conditions as sulphuric acid is commonly generated and metals display toxic effects when they are dissolved in acidic solutions (Williamson et al., 1982). The existence of dolomite arising from the natural background carbonate concentrations has the capacity to neutralise acidic conditions, but only in tailings containing 4 to 5% pyrite (Hinesly et al., 1972).

The concentrations of lead, zinc, copper and cadmium as outlined in Table 2 are excessive, particularly when compared with the maximum total values of 530, 720, 190 and 12 mg kg⁻¹, respectively, for normal soils as stipulated by the EPA (SRK, 2002). The solubility of these elevated metal levels would prove most detrimental if the pH of the tailings fell below 5.5 (Williamson et al., 1982), a consequence that is likely to develop in Gortmore TMF as acid generation is already prevalent in several areas of the facility. Furthermore, the organic matter content of the tailings is exceptionally low and this ensures that all plant micro- and macro-nutrients are in short supply (Williamson et al., 1982).

Table 1. Pyritic content of tailings (% weight) using the reference intensity ratio.

<table>
<thead>
<tr>
<th>% weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quartz</td>
</tr>
<tr>
<td>Calcite</td>
</tr>
<tr>
<td>Dolomite</td>
</tr>
<tr>
<td>Pyrite</td>
</tr>
<tr>
<td>Barite</td>
</tr>
<tr>
<td>Bassanite</td>
</tr>
<tr>
<td>Dioctahedral clay</td>
</tr>
</tbody>
</table>
PHYSICAL PROPERTIES

The values obtained for total porosity and bulk density (Table 3) are representative of grassland soils (Rowell, 1994), while the particle density is elevated in comparison to that of normal soils (2.65g cm\(^{-3}\)), owing to the heavy mineral content of the tailings and lack of organic matter (Williamson \textit{et al.}, 1982). The coarseness of the tailings may have been pivotal to the high porosity as sandy materials are generally unstructured and facilitate superior aeration and infiltration, but the ability of such substrates to retain water is poor, resulting in swift desiccation patterns (Davies, 1983).

CONCLUSIONS

The physical and chemical properties of the tailings are adverse to plant growth. Most conspicuous is the elevated pyrite and metal content and overall poor structural status of the tailings. These characteristics collectively pose great challenges in devising a sustainable reclamation scheme.

Referenced Publications


INTRODUCTION

Traffic-related road pollution, despite significant improvements in fuel and engine technology, has been recognised over the last century as the biggest single threat to air quality (Boddy et al., 2005). Pollution arising from road traffic within the EU was estimated to account for 54% of overall carbon monoxide (CO) emissions, 47% of nitrogen oxides (NOx) emissions and 29% of hydrocarbon (HC) emissions (Ekström et al., 2004). Within an Irish context, considering the period from 1990 to 2003, CO2 emissions increased from 4,642 kilotonnes (1990) to 10,993 kilotonnes (2003) (CSO, 2004). This is reflected in total number of vehicles, which increased from 1,054,259 (1990) to 1,937,429 (2004). Fossil fuel consumption over the same period grew by 53% (Faughnan, 2004).

Extensive measurements are in place to curb ever-increasing pollutant concentrations. This includes the EU air quality framework directive on ambient air quality. The EPA has responsibility for implementing international legislation at a national level. Local authorities are provided with guidelines and assistance on measures needed to ensure compliance with these EU directives (EPA, 2004), which include standard limits on ambient concentrations that if adhered to will avoid, prevent and reduce harmful effects on human health and the environment. Key tasks for compliance involve both monitoring and modelling of ambient air quality on both existing and proposed road developments. These are presented in the form of an environmental impact statement (EIS) by local authority bodies.

The CALINE4 line source model developed by the California department of transport is used in this study. The model predicts short-term CO concentrations at roadside sites (Benson, 1992). Budd et al. reviewed the selection of air quality models used on Irish EISs from 1990 to 1999, and identified CALINE4 as being used on a number of occasions. The main objectives of the study are to 1) assess the level of change in ambient air quality before and after the opening of the by-pass, and 2) assess the model’s short-term and long-term capabilities through comparison with monitored results from the site.

MONITORING METHODS

SITE

The monitoring campaign was conducted in the town centre of Monasterevin, Co Kildare, from October 2004 to January 2005. The monitoring unit, housing all the necessary equipment, was located at the Garda station to the north of the N7 road. The unit was positioned 10m from the centre of the road, behind a wall approximately 0.5m in height, as shown in Figure 1. The road is formed of two lanes catering for northbound and southbound traffic aligned east to west. The N7 is one of the busiest primary routes in the country, connecting the urban centres of Limerick and Cork with Dublin.

CARBON MONOXIDE MEASUREMENT

CO was measured using an API Model 300 gas filter correlation CO analyser. The basis of this method is infrared
(IR) spectroscopy. The diatomic molecule absorbs IR radiation by means of a series of molecular vibrations. Although IR analysis is more often employed as a qualitative tool in organic chemistry for deciphering what type of groups are in a molecule, it can also be used quantitatively for online continuous determinations. The sample is pulled across a critical flow orifice at a rate of 800 cm\(^3\) per minute. A broad band of IR radiation is produced by means of a high-energy heated element. This band of IR is then passed through a filter wheel, which directs radiation alternately to a reference and sample cell. The reference cell contains a CO/nitrogen mix and therefore absorbs IR at a steady rate, while the sample cell contains only nitrogen. Any reduction in IR intensity crossing the sample cell can be attributed to CO in the sample. The signal then passes on to a photomultiplier tube to allow conversion to a voltage signal. Two signals are produced by the measured and reference cells, and are proportional to the intensity of light striking the detector. Units are in COppm.

NITROGEN OXIDES MEASUREMENT

Nitric oxide (NO) and total NO\(_x\) were measured with an API Model 200a NO\(_x\) analyser, which determines nitrogen dioxide (NO\(_2\)) as the difference between the two measured concentrations. NO is measured from the light intensity of the chemiluminescent gas phase reaction of NO and O\(_3\). The reaction of NO and O\(_3\) produces oxygen and electronically excited NO\(_2\) molecules. These excited NO\(_2\) molecules give off photons of energy on returning to their ground state, which is specific to the concentration of NO. Any NO\(_2\) in the sample is then converted to NO by heated molybdenum and the total NO\(_x\) is measured.

PARTICULATE MATTER

Ambient concentrations of particulate matter of diameter ≤10 microns (PM\(_{10}\)) were measured using a Tapered Element Oscillating Microbalance series 1400a ambient particulate monitor. The method of analysis is based on the principle that the frequency of oscillation of a glass-tapered tube (element) changes by an amount that is proportional to the mass of the tube. Thus, any change in mass of the tube, due to deposition of particles onto a small filter affixed to one end, will result in a change of resonant frequency, which is proportional to the additional mass. To allow for uniform results independent of such variables as humidity and ambient temperature, the sample is heated to 50°C. This is a disadvantage over the classical gravimetric method, as semivolatiles may be lost. However, the unit does allow for continuous hourly measurement, unlike the gravimetric method.

METEOROLOGICAL AND TRAFFIC MEASUREMENT

Meteorological data comprising wind speed and wind direction were recorded on site. Met Éireann also provided wind speed, wind direction and Pasquill stability classes. These data were gathered at Casement Aerodrome, 40km north of Monasterevin and near the M7. The National Roads Authority provided hourly traffic data during the ‘before’ period. Manual counts were conducted during the ‘after’ period to assess the adjusted traffic volumes.

MODELLING METHODS

The USEPA-approved CALINE4 line source model was used for pollutant prediction. CALINE4 is a short-term (hourly) Gaussian dispersion model that requires hourly traffic data (traffic volume, emission factor) and meteorological data (wind speed, wind direction, atmospheric stability) to predict concentrations at receptor points downwind of source. Composite emission factors (CEFs) based on COPERT III data and a vehicle fleet profile of 85.6% passenger cars (diesel and petrol) and 14.4% goods vehicles (petrol and diesel light-duty vehicles, heavy goods vehicles) are presented in Table 1. Two sets of emission factors were used to reflect the different average vehicle speeds before and after the opening of the bypass. The section of road studied was modelled as three links. The background concentrations used in the model were taken as the measured hourly value that had the least traffic volume.

<table>
<thead>
<tr>
<th>Analyte</th>
<th>NO(_x)</th>
<th>CO</th>
<th>PM(_{10})</th>
</tr>
</thead>
<tbody>
<tr>
<td>CEF g/mile (25km/hr)</td>
<td>0.831</td>
<td>3.31</td>
<td>0.057</td>
</tr>
<tr>
<td>CEF g/mile (45km/hr)</td>
<td>0.672</td>
<td>2.05</td>
<td>0.035</td>
</tr>
</tbody>
</table>

RESULTS

TRAFFIC

The annual average daily traffic (AADT) before the opening was 24,106 vehicles, of which 4,060 (16.8%) were HGVs. The annual average peak flow was 1,898 vehicles per hour (vph), for the hour ending 18:00. The AADT for after the opening of the bypass was 11,982 vehicles, of which 719 (6%) were HGVs. The annual average peak flow was 984 vehicles for the hour ending 09:00.

METEOROLOGY

The prevailing winds at the monitoring unit were from the west, while the Met Éireann data showed that the prevailing winds were from the southwest. Stability class D was most frequent over the course of the study (81% of total hours). Stable conditions (classes E, F, G) never occurred between 09:00 and 16:00.
MEASURED CO

The measured before and after hourly averaged diurnal profiles for CO, shown in Figure 3, display an average reduction of 0.12 ppm CO. The maximum difference occurs at 10:00 (0.17 ppm CO), while the minimum difference occurs at 21:00 (0.07 ppm CO). Two peaks occurring at 09:00 and 18:00 can be attributed to peak traffic volumes occurring at these times (Figure 2).

MEASURED NOx

The measured before and after hourly averaged diurnal profiles for NOx show an average reduction of 23.7 ppb NOx with a maximum reduction of 44.6 ppb NOx at 07:00 and a minimum reduction of 8.9 ppb NOx at 16:00 (Figure 3).

MEASURED PM10

The measured before and after hourly averaged diurnal profiles for PM10 shown in Figure 5, display an average reduction of 4.2 µg/m³. The maximum reduction of 9.5 µg/m³ occurs at 13:00, while the minimum reduction of 1.6 µg/m³ occurs at 22:00 (Figure 4).

MODELLED CO

Both short-term (hourly) and long-term (over the duration of the monitoring period) model capabilities were analysed. On an hourly basis, the model is seen to perform quite well, with all the values being well within the ±50% limit for CO model accuracy (CEC, 1999, 2000). Figure 5 displays the diurnal profile for CO over the period of one sample day. The profile, however, is not well defined. Over a longer period, a distinct average diurnal profile emerges for both modelled and monitored data, as seen in Figure 6. The model over-predicts slightly during afternoon hours, but given the low levels of CO ambient concentrations, good performance by the model is observed overall.

Figure 3. Diurnal variation of measured NOx.
Figure 4. Diurnal variation of measured PM10.
Figure 5. Short-term measured and modelled CO concentrations.
Figure 6. Long-term measured and modelled CO concentrations.
Figure 7. Scatter plot of measured and modelled CO.
Figure 7 shows a scatter plot of the hourly measured and modelled concentrations for the 25/10/04. Reasonable correlation is seen between modelled and measured values. A general trend exists for the modelled concentrations (x) to increase or decrease proportionally to measured CO concentrations (y). A paired T-test was performed to see if there was a statistically significant difference between both sets of short-term data, i.e. modelled and measured. At a 95% confidence level, 23 degrees of freedom, the limits for our statistical model are ±2.07. A T-statistic of -0.4337 was calculated, which supports the conclusion that there is no statistical difference, other than random variation, between our data sets. Pearson’s correlation coefficient (R) 0.85 was also observed from the data analysis. A repeat T-test on the long-term data suggests a significant difference between both measured and modelled data, with a T-statistic of 4.41. Pearson’s correlation coefficient for the long-term data (R) was observed as 0.58.

DISCUSSION

COMPARISON OF MEAN POLLUTANT CONCENTRATIONS BEFORE AND AFTER OPENING OF THE BY-PASS

When compared, the mean concentrations for all pollutants show an improvement in air quality with respect to the reduced traffic volume attributable to the opening of the bypass (Table 2). The pollutant concentration that reduces the most is NOx with the before diurnal average concentration of 42.2ppb being reduced to 18.5ppb in the after case. CO also shows marked improvement with a before average concentration of 0.19ppm being reduced to 0.07ppm in the after case.

<table>
<thead>
<tr>
<th></th>
<th>CO (ppm)</th>
<th>NOx (ppb)</th>
<th>PM10 (µg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before</td>
<td>0.19</td>
<td>42.2</td>
<td>20.2</td>
</tr>
<tr>
<td>After</td>
<td>0.07</td>
<td>18.5</td>
<td>16.1</td>
</tr>
<tr>
<td>Difference</td>
<td>0.12</td>
<td>23.7</td>
<td>4.1</td>
</tr>
</tbody>
</table>

COMPARISON OF MODELLED AND MEASURED CONCENTRATIONS

The model predictions agree reasonably well for both measured short-term and long-term CO concentrations. Both sets of modelled data lie within ±50% of the measured values. The daughter directives (CEC, 1999, 2000) ‘allow 50% uncertainty in the modelling of eight-hour CO concentrations.’ The long-term average diurnal profile gives a better representation of CO concentration changes during a day. However, the model has been shown to provide statistically sound data in the short term. Although some form of bias is shown to exist in long-term measurements, in terms of pollutant concentration prediction, the model is deemed acceptable.

CONCLUSIONS

The improvement in air quality experienced due to the opening of a new town by-pass was assessed through air quality monitoring and dispersion modelling. Reductions in ambient pollutant concentrations of up to 50% were observed for some pollutants. It was shown that the use of site-specific input data in the CALINE4 model led to predictions of air quality that agreed well with the measured values, in both the short term and long term. These results suggest that accurate dispersion modelling can be used to predict changes in urban air quality due to major road developments.

REFERENCES


IMPACT OF BIOSTIMULANTS ON TURFGRASS GROWTH AND NUTRITION

T. Butler and A. Hunter

ABSTRACT

Turfgrass managers are under intense pressure to maintain excellent playing surfaces in the face of greater usage, wear and stricter environmental regulations. Many products have come on the market, with some claiming increased turfgrass performance through their use. This research was carried out in order to study the impact of some of these products on turfgrass growth, nutrition and health. Agrostis stolonifera cultivar ‘Penn A4’ seed was sown at a rate of 5g/m² in a sand:peat 85:15 v/v root zone (to USGA specifications) in a glasshouse at University College Dublin, in commercial 3l ‘Rose’ pots under supplementary heat and natural light conditions. Separate treatments of humic acid, seaweed extract and PHC organic plant feed were applied at their recommended rates on a bi-weekly basis. Additionally, humic acid/seaweed extract and humic acid/PHC organic plant feed combinations were also applied bi-weekly. Using ANOVA, PHC organic plant feed and PHC organic plant feed/humic acid treatments were shown to significantly increase grass fresh and dry weights. Grass colour was best in plants treated with PHC organic feed. Leaf tissue phosphorus levels were greatly elevated in plants treated with humic acid and PHC organic plant feed/humic acid. High tissue potassium levels were recorded in plants treated with humic acid and humic acid/seaweed extract. Leaching of phosphorus was high from all treatments. This research suggests that biostimulants may be useful in turfgrass management strategies, with PHC organic feed treatments showing particularly good grass growth and colour.

Key words: biostimulants, leachate, potassium, phosphorus, Agrostis stolonifera

INTRODUCTION

The environmental consequences of golf course construction and maintenance practices have captured much media attention in recent years. Unfortunately, most of the attention has been negative (Branham et al., 1995). Climatic conditions in Ireland together with current turfgrass maintenance recommendations create conditions that favour nutrient loss from applied fertilizers (Brown et al., 1982). One of the greatest fears is that the fertilizers used to maintain golf courses would pollute drinking water supplies, including both surface and groundwater sources. Many people are concerned about the potential effects of high nutrient and elevated pesticide levels in drinking water on human health (for example, on cancer), whilst concerns pertain to damage of surface waters and wildlife habitats (Snow and Kenna, 1999). Consequently, greenkeepers are constantly searching for new products to prevent or reduce these problems. One such development is the application of biostimulants to the turf. Biostimulants are products which, when used in small quantities, influence plant growth and development (Hamza & Suggars, 2001) through their ability to influence hormonal activity. Sea kelp, humic acids, plant hormones, sugar and organic products are common components of biostimulants (Hamza & Suggars, 2001; Long, 2004).

Plant hormones (phytohormones) are chemical messengers that regulate normal plant development such as root and shoot growth, together with environmental responses (Long, 2004). Compounds in biostimulants can alter the hormonal status of a plant and exert large influences over its growth and health (Long, 2004). Biostimulants contain metabolites that not only stimulate plant growth but also enhance the health status of plants, as they can suppress free radical activity which can damage plant cells (Long, 2004; Doyle, 2000). If a plant is not producing adequate endogenous amino acids, vitamins or hormones, the application of a biostimulant will substitute for their endogenous production (Doyle, 2000). Several products have been categorised as biostimulants, including humic acid, growth regulators, seaweed fertiliser and organic products (Isaac, 2000).

This research was initiated to investigate the effect of applying commercially available biostimulant products on turfgrass growth, nutrition, colour and leaching levels when applied to a sand-based root zone under reduced nutrient input levels.

MATERIALS AND METHODS

In November 2003, rose pots measuring 15cm x 18cm (3l) were filled with a root-zone mix (sand:peat 85:15 v/v) to USGA specifications, seeded with Agrostis stolonifera cultivar ‘Penn A4’ at a rate of 5g/m² and germinated under plastic in a glasshouse under natural light conditions and supplementary heating (15°C ±1°C) at the Horticultural Glasshouse Unit, Thornfield, University College Dublin. Prior to sowing, the seed was mixed with oven-dried sand to facilitate uniform seeding. Following germination, the plastic was removed and the grass was watered at 4 to 6-day intervals by hand throughout the duration of the experiment at a rate of 0.51 per pot per watering. Kemira liquid fertilizer was applied weekly to all of the treatments over the duration of the experiment at (0.075 g.l⁻¹.m⁻²). Separate treatments of seaweed extract (Marigrow), PHC organic plant feed (PHC) and humic acid (Root Enhance) were applied at bi-weekly intervals at their recommended rates of 2.0ml, 5.0ml and 0.75ml respectively, per m² commencing on 27 January 2004. Additionally, treatments containing mixtures of humic acid/seaweed extract and also humic acid/PHC organic plant feed were applied at bi-weekly intervals. The control pots received Kemira fertilizer at the above rate only. The nutrient analysis of the fertilizer and biostimulants used is given in Table 1 (source: Plant Health Care and National
Agrochemical Suppliers). The experiment was laid out as a completely randomised design with the grass pots being divided into six groups of twenty-four pots, with twenty-four pots representing a different treatment. Each group was sub-divided into three groups of eight. All of the pots were laid on growing benches within the glasshouse throughout the experiment and a perimeter guard row was placed around the pots.

Grass growth was measured on a weekly basis. Grass fresh weight was measured by cutting the grass to 20mm and weighing. Grass dry weights were also measured. Chlorophyll fluorescence of the grass was measured at the end of the experiment by ranking on a relative scale of Fv/Fm (variable fluorescence/maximum fluorescence) (Bjorkman & Demmig, 1987). Grass colour was evaluated subjectively at the end of the experiment using the National Turf Evaluation Program scale (1-9) (Petrovic et al., 2005), where 1 represented dead turfgrass, 6.5 minimal acceptable quality and 9 the optimum achievable quality. Leaf tissue analysis was carried out from grass cuttings, which were taken at the end of the experiment. Leaf phosphorus levels were determined colorimetrically whilst leachate potassium was determined using ICP.

At the end of the experiment, randomly selected soil samples were placed on absorbent paper, allowed to dry and used for soil analysis measurement. Soil phosphorus was determined colorimetrically. Soil potassium was determined using ICP. At the end of the experiment, the pots were irrigated with 700ml of public supply water to effect leaching by adding 100ml quantities every 30 seconds. The leachate was collected in clean receptacles. Leachate phosphorus was determined colorimetrically whilst leachate potassium was determined using ICP. Three pots from each group were selected randomly and the root mass was withdrawn and visually assessed for root structure.

### Table 1. Percent nutrients in each of the products applied

<table>
<thead>
<tr>
<th>% Nutrient</th>
<th>Marigrow</th>
<th>PHC</th>
<th>Kemira</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nitrogen</td>
<td>0.01</td>
<td>6.1</td>
<td>7.0</td>
</tr>
<tr>
<td>Phosphorus</td>
<td>0.02</td>
<td>5.2</td>
<td>2.7</td>
</tr>
<tr>
<td>Potassium</td>
<td>0.13</td>
<td>6.3</td>
<td>28</td>
</tr>
<tr>
<td>Boron</td>
<td>0.0006</td>
<td>0.028</td>
<td>0.028</td>
</tr>
<tr>
<td>Calcium</td>
<td>0.028</td>
<td>0.0092</td>
<td>0.015</td>
</tr>
<tr>
<td>Copper</td>
<td>0.001</td>
<td>0.21</td>
<td>0.15</td>
</tr>
<tr>
<td>Iron</td>
<td>0.065</td>
<td>4</td>
<td>0.07</td>
</tr>
<tr>
<td>Magnesium</td>
<td>0.0012</td>
<td>0.07</td>
<td>0.07</td>
</tr>
<tr>
<td>Zinc</td>
<td>0.0007</td>
<td>1.56</td>
<td>0.04</td>
</tr>
<tr>
<td>Sodium</td>
<td>0.04</td>
<td>7.6</td>
<td>6.3</td>
</tr>
<tr>
<td>Sulphur</td>
<td>0.04</td>
<td>7.6</td>
<td>6.3</td>
</tr>
</tbody>
</table>

Table 2. Analysis of variances for biostimulant effects on turf grass fresh weight, grass dry weight, grass colour, chlorophyll fluorescence, tissue P, tissue K, leachate P, leachate K.

### Table 2. Analysis of variances for biostimulant effects on turf grass fresh weight, grass dry weight, grass colour, chlorophyll fluorescence, tissue P, tissue K, leachate P, leachate K.

<table>
<thead>
<tr>
<th>Biostimulant</th>
<th>Fresh Weight</th>
<th>Dry Weight</th>
<th>Grass Colour</th>
<th>Chlorophyll fluorescence</th>
<th>Tissue P</th>
<th>Tissue K</th>
<th>Soil P</th>
<th>Soil K</th>
<th>Leachate P</th>
<th>Leachate K</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td><em>59.50a</em></td>
<td>19.60a</td>
<td>6.91a</td>
<td>0.82a</td>
<td>0.24a</td>
<td>0.55b</td>
<td>20.00b</td>
<td>62.50a</td>
<td>0.18a</td>
<td>7.23b</td>
</tr>
<tr>
<td>Humic acid</td>
<td>72.10b</td>
<td>25.90b</td>
<td>6.80a</td>
<td>0.83a</td>
<td>0.30b</td>
<td>1.51d</td>
<td>21.08b</td>
<td>70.15b</td>
<td>0.77e</td>
<td>8.45c</td>
</tr>
<tr>
<td>Seaweed extract</td>
<td>70.00b</td>
<td>25.55b</td>
<td>6.60a</td>
<td>0.79a</td>
<td>0.28ab</td>
<td>0.57b</td>
<td>14.75a</td>
<td>67.12a</td>
<td>0.22b</td>
<td>4.68a</td>
</tr>
<tr>
<td>Humic/Seaweed</td>
<td>63.70a</td>
<td>24.50b</td>
<td>6.66a</td>
<td>0.78a</td>
<td>0.24a</td>
<td>2.01e</td>
<td>15a</td>
<td>80.00d</td>
<td>0.19a</td>
<td>7.47b</td>
</tr>
<tr>
<td>PHC</td>
<td>90.23c</td>
<td>29.75c</td>
<td>8.50b</td>
<td>0.84a</td>
<td>0.27ab</td>
<td>0.50a</td>
<td>30.3d</td>
<td>70.00bc</td>
<td>0.28c</td>
<td>7.33b</td>
</tr>
<tr>
<td>PHC/Humic acid</td>
<td>93.10c</td>
<td>30.31c</td>
<td>8.32b</td>
<td>0.77a</td>
<td>0.35c</td>
<td>1.25c</td>
<td>22.85c</td>
<td>74.65c</td>
<td>0.33d</td>
<td>15.55d</td>
</tr>
<tr>
<td>SED</td>
<td>2.05</td>
<td>0.89</td>
<td>0.33</td>
<td>0.04</td>
<td>0.02</td>
<td>0.01</td>
<td>0.76</td>
<td>2.25</td>
<td>0.05</td>
<td>0.35</td>
</tr>
<tr>
<td>LSD</td>
<td>4.52</td>
<td>1.96</td>
<td>0.73</td>
<td>n/s</td>
<td>0.04</td>
<td>0.03</td>
<td>1.67</td>
<td>4.95</td>
<td>0.1</td>
<td>0.77</td>
</tr>
</tbody>
</table>

* Indicates significance at P = 0.05. Within a column, means followed by the same lower-case letter are not significantly different according to Fishers LSD (P=0.05).
soil phosphorus concentration significantly compared to all other treatments (Table 2). Soil potassium levels were lowest in control treatments with potassium levels of 62.5 mg.kg\(^{-1}\) (Table 2). Humic acid treatments and PHC/humic acid treatments significantly increased soil potassium compared to both the control and seaweed extract treatments.

The application of humic acid did not prevent phosphorus leaching from the root zone. In fact, treatments of humic acid resulted in significantly higher phosphorus levels than control treatments with a phosphorus concentration in the leachate of 0.77 mg.kg\(^{-1}\). The control, seaweed extract and humic acid/seaweed extract treatments had significantly lower leachate phosphorus concentrations than all other treatments (Table 2). The highest levels of potassium were found in the leachate of PHC/humic acid treated plants, with potassium levels of over twice that of control treatments being recorded. Seaweed extract treatments gave the lowest leachate potassium concentration. No significant differences in leachate potassium concentration were found between the control, humic acid/seaweed extract and PHC treatments.

When the root systems of plants from each treatment were examined, there were no detectable differences observed in root lengths, irrespective of treatment.

**DISCUSSION AND CONCLUSIONS**

PHC and PHC/humic acid treatments significantly increased the fresh weight of the grass. This establishes that both these treatments increase grass vigour. Tissue phosphorus, soil phosphorus and potassium, and leachate phosphorus, results suggest this, because both the PHC and PHC/humic acid treatments significantly increased these results compared to the control treatment for all of these measurements. Combining the results shows that if PHC is to be used on a golf green, then the level of inorganic fertilizers should be reduced to prevent excessive grass growth and leaching (Hunter et al., 2003). Such “soft” growth could lead to a disease outbreak. Dry weight accumulation showed similar results.

Grass colour is a critical component in turfgrass management. The results show that treatments of PHC and PHC/humic acid give very dark green swards. However, the remaining treatments give poor colour scores, which under highly trafficked turf may not be acceptable. Colour is a useful visual indicator of the general condition of the plant (Turgeon, 2002; Beard, 2005) and poor colour may indicate reduced stress tolerances in the grass plant. The poor colour is related to the reduction in fertilizer rate used in the experiment. Thus, if these products are to be used on turfgrass, then supplementary treatments such as iron will be required to enhance grass colour. Thus, the use of PHC and PHC/humic acid can be used under reduced fertilizer input systems.

Although objective analysis of grass colour indicated differences between treatments, this was not detected from the chlorophyll fluorescence results. This demonstrates that fluorescence can be maximised even when grass colour appears to be less than optimal.

The desired phosphorus level in leaf tissue ranges between 0.3–0.55 % (Lawson, 1996). Treatments of PHC/humic acid provided the highest phosphorus values of 0.35%. The research shows that the above products encourage greater uptake of phosphorus in the tissue and thus can partially substitute for elemental phosphorus application to the sward. Treatments of humic acid, humic acid/seaweed extract and PHC/humic acid gave tissue potassium levels within the sufficiency range of 1.0–2.5 % (Lawson, 1996). All of the other treatments were below the recommended values and, if used on a course, would require supplementation. The potassium levels were surprisingly low in plants treated with PHC. This may suggest that the PHC treatment had a negative effect on the plants’ ability to take up applied potassium. Potassium is often called the “health element” because an ample supply helps to increase turf tolerance to heat, cold, drought, disease and wear (McCarty et al., 2003). Thus, all grass plants receiving treatments which gave potassium concentrations below 1% may have been weakened. In agreement with Beard (1973), Goss & Gould (1968) and Markland et al. (1967), turfgrass wear tolerance, turfgrass red thread, and dollar spot resistance is reported to be increased proportionally with the potassium level (Beard, 1973). This application of humic acid and humic acid/seaweed extract treatments may be a useful tool in turfgrass management to improve wear tolerance and reduce disease.

All of the treatments yielded soil phosphorus levels above the recommended levels, with plants treated with PHC Organic Plant feed yielding soil phosphorus levels almost four times the recommended levels. This finding concurs with that previously reported by Hunter et al. (2003). This high phosphorus level could have a negative effect on golf greens because it is widely known and accepted that high levels of phosphorus may encourage the development of Poa annua (Turner & Hummel, 1992). Root-zone potassium concentrations were low, however, regardless of treatment. Humic acid/seaweed extract treatments yielded the highest at 80 mg.kg\(^{-1}\) potassium. Potassium can be lost from the soil through leaching, with losses through drainage for an A. stolonifera sward (grown on sand) being in the order of 52% (Beard, 1973). Leaching losses can be substantial in sandy soils, since potassium salts are readily soluble in water. In most clay soils (with high clay content) potassium is retained in large quantities (Turgeon, 2002). This coupled with the reduced fertilizer programme possibly accounts for the low levels of potassium in the root zone of all treatments. One beneficial effect from this could be that such low potassium levels are beneficial in late spring/early summer, since there is accepted evidence to suggest that low potassium levels at this time of year help control seed head production in Poa annua.

All of the treatments gave phosphorus leachate values significantly greater than the permissible EU value of 0.03 mg.kg\(^{-1}\). This agrees with the findings of Hunter et al. (2003) who found phosphorus levels (in leachate from a root zone to USGA specification) of up to 1,000 times that of the EU permissible level. Very little difference was noted in the level of phosphorus leaching from treatments except for humic acid treatments, which yielded 0.77 mg.kg\(^{-1}\). This suggests that phosphorus is readily leached from all of the treatments but especially where humic acid was applied. From the findings, it is shown that as phosphorus levels are increased to bring tissue levels up towards the recommended sufficiency levels, it is not readily available to the plant but instead is lost to the environment. Thus, the recommended sufficiency levels as published could be excessive, in particular since the fluorescence tests failed to elicit any perceived deficiency problems. High potassium leachate levels were found in plants treated with PHC/humic acid. These leachate values are well above the other treatments and it is clear that the level of potassium within the root zone of plants treated with these products is excessive. The results show that inorganic potassium levels could better be supplied in association with seaweed extract, possibly because seaweed extract may increase the root density in the soil, which is very important in minimising leaching concentrations.

From the experiment, it appears that none of the treatments impacted on the length of the root system. This was interesting because humic acid has been found to increase root growth in other crops such as wheat and carrots (Sanders et al., 1990; Malik and Azam, 1985).

The research findings suggest that application of PHC organic plant feed is useful in increasing grass growth, colour and tissue potassium in turgrass plants. Seaweed acid use in turgrass swards may be a
possible method to reduce potassium losses through leaching.

ACKNOWLEDGMENTS

The authors would like to express their sincere appreciation to Mr Ray O’Haire for his contribution to this project and to Mr Tom Moore and Ms Anne Killion for assistance with laboratory analysis.

REFERENCES


A SOLID PHASE EXTRACTION AND HIGH PERFORMANCE LIQUID CHROMATOGRAPHY METHOD FOR THE DETECTION OF PHARMACEUTICAL COMPOUNDS

Clair Lacey, Gillian McMahon, Jonathan Bones, Leon Barron, Anne Morrissey and John Tobin

ABSTRACT

The possible effect of pharmaceutical compounds on living organisms in the aquatic environment has become a growing concern in recent years. Pharmaceutical substances are currently not required to undergo the same level of testing as pesticides for possible environmental effects and impacts on living systems. Consequently, they and their metabolites have been emitted unrestrictedly, primarily into waterbodies, for many years. New research in the EU and US has quantified the extent of this problem in selected river/water systems and shown that significant environmental impacts are occurring.

The overall purpose of this research is to assess the presence and concentration of a range of pharmaceuticals in influent and effluent of three Irish sewage treatment plants (STP) and determine the potential health impacts on aquatic and terrestrial organisms. To date, twenty-two pharmaceutical compounds have been identified for analysis and a HPLC method has been developed for the separation and identification of these compounds in aqueous samples. Details of this method are presented here.

INTRODUCTION

The presence of pharmaceuticals and personal care products (PPCPs) in the aquatic environment is an emerging area of environmental concern (Huber et al., 2003). Richardson & Bowron (1985) were one of the first to suggest that PPCPs entering the environment could have both a health and environmental impact. They proposed that human pharmaceuticals could potentially enter the environment via two routes as later illustrated in Figure 1 (Diaz-Cruz, M.S. et al., 2003; Halling-Sorensen, B., et al., 1998): (1) disposal, such as point discharge to waste water treatment plants from pharmaceutical manufacturing plants, and (2) excretion after human use. In the former case, due to strict regulatory guidelines, product lost to drain is low compared to other industries, at 1-5%, although this is still environmentally significant.

The presence of PPCPs in the environment was not investigated in detail until the late 1990s, with the development of new technologies capable of detecting analytes at low concentrations. These technologies included multi-method analytical techniques such as solid-phase extraction followed by liquid chromatography (tandem mass spectrometry) or gas chromatography (tandem mass spectrometry). Since then, numerous compounds, including those listed in Table 1, have been detected in sewage treatment plant effluent, surface water, groundwater and drinking water supplies in recent years (Ternes, 1998; Andreozzi et al., 2003; Christensen, 1998).

Little research has been undertaken to date to identify whether the presence of pharmaceuticals represents an environmental risk for Ireland. Many pharmaceuticals routinely detected in the environment in other countries are among the top 100 prescribed products in Ireland (Irish Medicines Board, 2003). These include ibuprofen, mefenamic acid, carbamazepine and diclofenac.

Ideally, pharmaceutical compounds that enter the environment would be completely biodegraded. However,
because pharmaceuticals are designed to be highly stable, lipophilic and potent molecules, they tend to persist in the environment. The presence of pharmaceutical compounds in the environment is also assisted by their continual input to the environment.

The entry of specialty compounds, designed for use in human and veterinary medical practices, to ground and surface water depends on a number of interconnected factors, such as pharmaceutical consumption rates, behaviour in STPs and the ability of receiving waterbodies to provide adequate dilution. Pharmaceuticals used for medicinal purposes are not entirely metabolised in the body and up to 90% can be excreted either as the parent compound, metabolite or conjugate (Castiglioni et al., 2005; Daughton and Ternes, 1999; Drilla et al., 2005). Sewage treatment is often not adequate for the removal of pharmaceutical residues, resulting in the active compound being discharged to the receiving waterbody (Hoeger et al., 2005; Boyd et al., 2003). The fate of specific pharmaceutical compounds in STPs depends on the characteristics of the sewage, weather conditions and the design and operation of treatment processes (Boyd et al., 2003). Veterinary medicinal products, once administered, are either excreted directly onto the land or, in the case of housed animals, collected and spread as manure at a later date. Leachate from the soil allows for entry to groundwater. Approximately 70% of unused or expired pharmaceuticals are disposed of in domestic bin waste which ultimately ends up in landfill or discarded via the sewage system, thereby increasing the environmental load of pharmaceuticals (Daughton & Ternes, 1999; Slack, et al., 2005).

The analysis of pharmaceutical compounds in environmental samples has been achieved by a variety of analytical methods, including both gas chromatography (GC) and liquid chromatography (LC) coupled with mass spectrometry (MS) (Thomas & Hilton, 2004; Tauxe-Wuersch et al., 2005; Stumpf et al., 1999; Hernandez et al., 2004). The majority of pharmaceutical compounds contains polar functional groups which have a low volatility or thermal stability. This means that they cannot be detected directly and a derivatisation step is required prior to GC analysis. On the other hand, LC allows for the direct determination of polar compounds and reduces the risk of variability in results (Ternes, 2001). MS is used to confirm the identification of analytes based on their mass to charge ratio (m/z). For this reason, LC-MS was selected as the preferred analytical method for the detection of extremely low concentrations of pharmaceuticals in wastewaters.

The aim of this work was to develop a High Performance Liquid Chromatography (HPLC) method for the separation of a range of pharmaceutical compounds from a variety of therapeutic classes.

**MATERIALS AND METHODS**

Pharmaceuticals were categorised into two groups for the purpose of analysis (Table 1). Group I consists primarily of acidic compounds while group II is made up of basic compounds.

**MATERIALS**

Methanol, acetonitrile, acetonitrile with 0.1% ammonium acetate and water with 0.1% ammonium acetate were purchased from Sigma-Aldrich, Dublin, Ireland, of HPLC grade or LC-MS grade. Formic acid, dichloromethyilsilane and toluene used were analytical grade and also purchased from Sigma-Aldrich, Dublin, Ireland.

The following standard materials (all >95% pure) were sourced as follows: metformin hydrochloride, salicylic acid, propranolol hydrochloride, clofibric acid, ketoprofen, clotrimazole, diclofenac sodium salt and carbamazepine were obtained from Aldrich (Steinheim, Germany). Caffeine, trimethoprim and naproxen were obtained from Fluka (Buchs, Switzerland) and bezafibrate, flurbiprofen, indomethacin, ketoprofen, atenolol, sulfamethoxazole, metoprolol, ibuprofen sodium salt, mefenamic acid and gemfibrozil were obtained from Sigma (Steinheim, Germany). Water (0.1% ammonium acetate) and methanol (0.1% ammonium acetate) used were supplied by Riedel-de Haen (Germany). Strata X 200mg/6ml SPE columns were obtained from Phenomenex, UK; C8, C18 and LiChrolut 300mg SPE columns were obtained from Sigma (Steinheim, Germany). Oasis HLB 6cc columns were supplied by Waters (Ireland).

1000mg/l stock solutions of each analyte were prepared in methanol and stored at 40°C in the dark for optimum stability. Working standards were prepared by dilution using methanol from these stock solutions.

**GLASSWARE PREPARATION**

All glassware used was silanised by rinsing them thoroughly with a 10% (v/v) solution of dichloromethylsilane in toluene followed by two toluene rinses and then two methanol rinses. This was to prevent any pharmaceutical residue from adsorbing to the glassware.

<table>
<thead>
<tr>
<th>Group I</th>
<th>Therapeutic Class</th>
<th>Group II</th>
<th>Therapeutic Class</th>
</tr>
</thead>
<tbody>
<tr>
<td>Salicylic Acid</td>
<td>Metabolite</td>
<td>Metformin</td>
<td>Anti-diabetic</td>
</tr>
<tr>
<td>Ketoprofen</td>
<td>Anti-inflammatory</td>
<td>Atenolol</td>
<td>Cardiovascular</td>
</tr>
<tr>
<td>Naproxen</td>
<td>Anti-inflammatory</td>
<td>Sulfinamethoxazole</td>
<td>Sulfonamide</td>
</tr>
<tr>
<td>Clofibric Acid</td>
<td>Lipid regulator</td>
<td>Caffeine</td>
<td>C.N.S. stimulant</td>
</tr>
<tr>
<td>Bezafibrate</td>
<td>Lipid regulator</td>
<td>Trimethoprim</td>
<td>Bacteriostatic antibiotic</td>
</tr>
<tr>
<td>Flurbiprofen</td>
<td>Anti-inflammatory</td>
<td>Metoprolol</td>
<td>b-blocker</td>
</tr>
<tr>
<td>Diclofenac</td>
<td>Anti-inflammatory</td>
<td>Propranolol</td>
<td>b-blocker</td>
</tr>
<tr>
<td>Indomethacin</td>
<td>Anti-inflammatory</td>
<td>Carbamazepine</td>
<td>Anti-convulsant</td>
</tr>
<tr>
<td>Ibuprofen</td>
<td>Anti-inflammatory</td>
<td>Clofibrate</td>
<td>Anti-fungal</td>
</tr>
<tr>
<td>Mefenamic Acid</td>
<td>Anti-inflammatory</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gemfibrozil</td>
<td>Lipid regulator</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Table 1. Group I and Group II pharmaceuticals for analysis.**
METHODS

SAMPLE PRECONCENTRATION

Solid phase extraction was used for the preconcentration of standard samples. Five different cartridges were compared for the optimal recovery of the selected analytes. Prior to extraction the solid phase cartridges were washed with three column volumes of methanol followed by three column volumes of water to prepare the matrix. 1l samples were adjusted to pH 2 using formic acid and then introduced to the column under vacuum. The column was dried under vacuum following sample addition. Analytes were eluted from the cartridge with 10ml of methanol. After elution, samples were dried under nitrogen, resuspended in methanol to a volume of 1ml and analysed by HPLC.

HIGH PERFORMANCE LIQUID CHROMATOGRAPHY

The liquid chromatography system used was a Varian inert 9012 solvent delivery system, a Dynamax automatic sample injector model AI-200 and a Varian 9050 variable-length UV-VIS detector. Separation was achieved using a 150mm x 4.6mm end-capped YMC C18 3µm reversed phase HPLC column (YMC Europe GmbH, Germany).

Optimum separation was achieved using gradient elution, 0.1% ammonium acetate in water (pH 6.2) and 0.1% ammonium acetate in methanol at a flowrate of 1ml min⁻¹. A 20 µL injection volume was employed.

Absorbance was monitored at 225nm, which was the determined optimum in preliminary studies.


Table 2. Gradient for HPLC separation.

<table>
<thead>
<tr>
<th>Time (min)</th>
<th>% Water (0.1% ammonium acetate)</th>
<th>% Methanol (0.1% ammonium acetate)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>90</td>
<td>10</td>
</tr>
<tr>
<td>2</td>
<td>90</td>
<td>10</td>
</tr>
<tr>
<td>25</td>
<td>10</td>
<td>90</td>
</tr>
<tr>
<td>35</td>
<td>10</td>
<td>90</td>
</tr>
</tbody>
</table>

Flow rate: 1.0 ml min\(^{-1}\)

RESULTS AND DISCUSSION

SAMPLE PRECONCENTRATION

Selected SPE columns were examined for recovery of the pharmaceutical compounds. They included Strata X, C8, C18, Oasis HLB and LiChrolut. Recovery of analytes from the five cartridges ranged significantly. Salicylic acid was poorly retained by C8, C18 and LiChrolut, with recoveries of 5.7, 16.3 and 38.9% respectively, while Strata X and HLB both gave recoveries of greater than 90%. HLB and Strata X gave comparable high recoveries for all analytes. Strata X columns were selected for further investigations as they yielded better recovery for the majority of compounds overall.

HIGH PERFORMANCE LIQUID CHROMATOGRAPHY

Initial experiments investigated the starting conditions of the mobile phase. Results showed that a starting mobile phase of 10% methanol increased the retention time of compounds such as salicylic acid, atenolol and metformin. An increase to 90% methanol over a twenty-three minute period allowed for the complete separation of all of the analytes investigated. The gradient employed for this separation is shown in Table 2. Baseline separation and good peak shape was attained for five of the compounds in group I, while all compounds in group II were baseline-resolved, as shown in Figures 2 and 3.

CONCLUSION

An analytical method has been developed for the preconcentration and subsequent separation of a range of pharmaceutical compound. Preconcentration was obtained using Strata X SPE columns while separation and identification of analytes was achieved using a HPLC separation with UV detection. Future work will involve coupling the HPLC method with mass spectrometric detection to improve the specificity, selectivity and sensitivity of the method.

ACKNOWLEDGMENTS

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REFERENCES


APPROACHES TO ENHANCE THE LIQUID CHROMATOGRAPHIC DETERMINATION OF PHTHALATES IN ENVIRONMENTAL MATRICES

Antoinette M. Reid, Concepta A. Brougham, Andrew M. Fogarty and James J. Roche

ABSTRACT

An improved liquid chromatographic (HPLC) method has been developed for the determination of selected phthalate esters in aqueous environmental matrices. It proved possible to exploit the p-p interactions of a bonded phenyl stationary phase to give an acceptable separation for key selected analytes, which also contained an aromatic moiety. Coupled with the enhanced baseline stability of an isocratic flow, the utilisation of narrow-bore column hardware and prior concentration enrichment using solid-phase extraction (SPE), extremely low limits of detection were achieved. The implications of this were that it proved possible to report on the relatively low levels of these substances at selected points along the River Shannon, this being the longest river in the British Isles, yet one that passes through a region of low population density. This watercourse is world-renowned for its angling, leisure and tourism activities but its basin also features an unusually high concentration of polymer-based healthcare manufacturing facilities. A screening study of phthalate-based plasticisers was therefore indicated. Amounts of phthalates at the sub-µg/L level were found in the matrices tested.

Key words: plasticisers, phthalate esters, oestrogenic, solid-phase extraction

INTRODUCTION

Phthalates are used as plasticisers but also in industrial paints, inks, adhesives, dielectric fluids, defoaming agents, lubricating oils, insect repellents and cosmetics. An estimated 90% of plasticisers manufactured are used in PVC, and Tarrant et al. (2005) determined imports of phthalates into Ireland to be 20,000 tonnes per year. Normally, a flexible PVC product will contain between 20% and 50% plasticiser. Di-2-ethylhexyl phthalate (DEHP) accounts for 90% of all plasticiser usage in Europe (Turner & Rawling, 2000). In relation to hormonally active agents, chemicals with oestrogenic activity are causing concern as they are being linked with serious reproductive effects in aquatic organisms. The human oestrogen receptor (ER) consists of a ligand binding domain for 17 b-oestradiol which is considerably larger than the oestradiol molecule, allowing space for a variety of other molecules to interact with the ER, which gives rise to oestrogen mimicking. Phthalate plasticisers are one group of chemicals capable of such interaction (Hashimoto et al., 2003). Recently, the possible health hazards of DEHP, di-isomonyl phthalate (DINP) and di-isodecyl phthalate (DIDP) have been examined (Kambia et al., 2003; Earls et al., 2003; Pietrogrande et al., 2003). DEHP and dibutyl phthalate (DBP) are suspected testicular and ovarian toxicants, whilst other phthalates are considered to be either hepatic or embryo foetal toxicants (Wams, 1987; Nascimento Filho et al., 2003).

Phthalate esters, leaching from landfill, waste to groundwater via the soil and to surface-water bodies through leachate runoff, represent a significant source. Martinen et al. (2003) found the highest levels of phthalates leaching from operating landfills and to a slightly lesser extent from closed landfills. In this study, a method for the separation of DBP, DEHP, DINP and DIDP, using isocratic reversed-phase (RP) HPLC, was developed. Surface water samples were taken at various locations along the length of the River Shannon, targeting areas in the vicinity of effluent discharges, leachate or industrialised conurbations. The objective was to develop a method capable of detecting trace and ultra-trace levels to the ng/L range and, following this, to establish levels of phthalates present in the border, midlands and western (BMW) region of the Irish aquatic environment.

MATERIALS AND METHODS

CHEMICALS AND REAGENTS

All reagents were of analytical grade. The following were purchased from Sigma-Aldrich (Ireland): dibutyl phthalate (DBP) >98%; di-2-ethylhexyl phthalate (DEHP) 99%; diisononyl phthalate (DINP) >99%; and di-isodecyl phthalate (DIDP) >99%. HPLC grade methanol, dichloromethane, acetonitrile and ethyl acetate were purchased from Labscan Analytical Ltd (Ireland). SPE disks from 3M-Empore were purchased from Varian through JVA Analytical (Ireland) and 47mm microfibre glass filters GF/C (1.2µm) and GF/F (0.7µm) and nylon (0.45µm) were purchased from AGB Scientific (Ireland). Serially diluted solutions of analyte mixtures of the primary stock solutions were carried out in the appropriate HPLC grade solvent as required on a daily basis. Primary stock solutions were prepared individually from the pure compound at a concentration of 100 mg/L and were stored in amber glass bottles at 4°C, remaining stable for at least eight months.

ANALYTICAL PROCEDURE

The use of a low-pressure gradient delivery system allowed us to study the retention characteristics of the analytes during method development, and optimum sensitivity was achieved through a related isocratic procedure. Chromatographic measurements were performed on a modular liquid chromatographic system consisting of Waters Autosampler 717, Waters Pump 510, and Shimadzu LC-6AD Detector set at 226nm, a Pinnacle II Phenyl (150 x
2.1mm, 5mm) column and equivalent guard column that were purchased from Restek Ireland. The column combined the use of a narrow bore configuration containing a phenyl-packing material.

RESULTS AND DISCUSSION

METHOD VALIDATION

Using an RP gradient HPLC method combined with SPE for environmental analysis, Jen et al. (2006) developed a method for the separation of dimethyl-, diethyl- and dibutyl phthalate with respective limits of detection of 12.2, 7.0 and 15.7 µg/L. Another method developed by De Orsi et al. (2006) for analysis of phthalates in cosmetics showed LOD values for DBP and DEHP and DINP of 0.4, 0.5 and 0.6 µg/mL respectively. However, we have developed a method, which is more sensitive than existing methods, as we can see from the limit of detection values in Table 2 where limits in the parts per billion range and below have been reached. Log P measurements as determined by ACD Log D Suite (purchased from Adept Scientific, UK), show the degree to which the compound is partitioned between water and octanol (or other non-miscible solvent), i.e. the Log Kow is a measure of lipophilicity. From the table we can see that DBP is the most soluble in water, whilst DIDP will be the least soluble, the most lipophilic and will have a greater likelihood for partitioning and bioaccumulation in the body. The capacity factor is an important parameter that is commonly used to describe migration rates of analytes on columns. A large capacity factor favours good separation but may increase elution time, so a compromise between the two is needed. An ideal value is between 2-10, although this depends on the number of analytes and their respective affinity for the phases.

In unpublished work, all possible laboratory contaminants were identified prior to executing the sampling plan. The uses of plastic apparatus or equipment shown to contain phthalates were avoided. Results from analysis of contamination sources also identified contamination from SPE syringe barrels leading to the preferred usage

<table>
<thead>
<tr>
<th>River</th>
<th>Selection criteria based on proximity to potentially contributing sources</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>D/S STP</td>
</tr>
<tr>
<td>Camlin (Longford)</td>
<td>√</td>
</tr>
<tr>
<td>Shannon (Lanesborough)</td>
<td>√</td>
</tr>
<tr>
<td>Hind (Roscommon)</td>
<td>√</td>
</tr>
<tr>
<td>Shannon (Athlone)</td>
<td>x</td>
</tr>
<tr>
<td>Grand Canal (Shannon Harbour)</td>
<td>x</td>
</tr>
<tr>
<td>Shannon (Banagher)</td>
<td>x</td>
</tr>
<tr>
<td>Nenagh (Annabeg, Tipperary)</td>
<td>√</td>
</tr>
<tr>
<td>Shannon ‘Longpavement’ (Limerick)</td>
<td>√</td>
</tr>
</tbody>
</table>

Note: D/S = downstream, STP = sewage treatment plant.

<table>
<thead>
<tr>
<th>Analyte /CAS RN</th>
<th>Molecular formula and M&lt;sub&gt;w&lt;/sub&gt;</th>
<th>Retention time (R&lt;sub&gt;t&lt;/sub&gt;) /alkyl chain length</th>
<th>Aqueous solubility (µg/mL) (Tarrant et al., 2005) /Log P</th>
<th>Linearity multiple regression coefficient (r&lt;sup&gt;2&lt;/sup&gt;) /SPE recovery value (%)</th>
<th>LOQ with % RSD ≥ 20% (ng/L) /LOD (ng/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DBP /84-74-2</td>
<td>C&lt;sub&gt;16&lt;/sub&gt;H&lt;sub&gt;22&lt;/sub&gt;O&lt;sub&gt;4&lt;/sub&gt;</td>
<td>4.6 /4/1.56</td>
<td>/11.2 /4.83 ± 0.25</td>
<td>0.99 /73.0</td>
<td>40.0 /22.0</td>
</tr>
<tr>
<td>DEHP /117-81-7</td>
<td>C&lt;sub&gt;24&lt;/sub&gt;H&lt;sub&gt;38&lt;/sub&gt;O&lt;sub&gt;4&lt;/sub&gt;</td>
<td>9.9 /8/4.56</td>
<td>/0.003 /8.71 ± 0.26</td>
<td>0.98 /83.6</td>
<td>40.0 /28.4</td>
</tr>
<tr>
<td>DINP /28553-12-0</td>
<td>C&lt;sub&gt;26&lt;/sub&gt;H&lt;sub&gt;42&lt;/sub&gt;O&lt;sub&gt;4&lt;/sub&gt;</td>
<td>12.5 /9/6.05</td>
<td>/&lt;0.001 /9.77 ± 0.26</td>
<td>0.98 /114.8</td>
<td>400.0 /52.8</td>
</tr>
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<td>DIDP /26761-40-0</td>
<td>C&lt;sub&gt;28&lt;/sub&gt;H&lt;sub&gt;46&lt;/sub&gt;O&lt;sub&gt;4&lt;/sub&gt;</td>
<td>14.9 /10/7.50</td>
<td>/&lt;0.001 /10.83 ± 0.26</td>
<td>0.99 /84.0</td>
<td>800.0 /51.2</td>
</tr>
</tbody>
</table>

Note: LOD = Limit of Detection, LOQ = Limit of Quantitation, RDS = % relative standard deviation. The linear range was 0–1 µg/mL.
of disks. Recovery SPE experiments utilising a variety of eluting solvents was carried out in order to choose the most efficient solvent for elution. The use of ethyl acetate was the preferred solvent as it eluted less humic matter, hence improving chromatographic results significantly and subsequently exerting less hardship on the guard column. When using disks, the wash was collected together with the two final volumes of eluting solvent as experimental work showed that washing removed some of the target analytes. SPE was carried out on 500 mL samples of river, leachate and effluent. The sites and matrices examined for the study were chosen carefully, taking into consideration their significance in terms of anthropogenic activity, targeting landfills, urbanised locations, boating areas and the immediate surroundings of these locations. Samples were taken and analysed from various locations along the River Shannon including its tributaries. The sampling process was carried out using an inert stainless steel telescopic sampling rod and sampling cup. Samples were then collected into 2.5L amber glass bottles and stored in a cool bag with ice packs and transported to the laboratory immediately. Sample extracts were evaporated to dryness at 37°C under nitrogen and were reconstituted in 200µL of acetonitrile prior to injection of 5µL. The use of a reconstituting solvent stronger than the mobile phase is usually avoided but was employed in this case to facilitate dissolution and was compensated for by the relatively small injection volume. No effect on peak structure was observed and separations with resolution values of up to 2.85 were achieved for the four phthalates using a flow rate of 0.2 mL/min and a mobile phase of 30:70 water:acetonitrile. Table 3 illustrates the concentrations found in a single month of two phthalates at all of the locations.

We can see from Figure 1 that there is no discriminating change between the locations, and levels appear to be within 0.14-2.74 mg/L for both compounds. Organic pollutants will bind to dissolved solids and particulate matter, increasing their solubility. For instance, in Table 3, DINP was detected in Lanesborough at 2.07µg/L during May, this value being approximately twice the value of the solubility temperature reported by Tarrant et al. (2003), even though the temperature on sampling was just 11.4°C. Log Kow for DINP is high, meaning that solubility will be low but ability to adsorb to solids is high. DINP will be readily sorbed onto dissolved organic matter also, so in warmer weather there will be higher levels of target analytes determined because the bioavailability of the analytes increases.

As anticipated, DEHP proved to be the most prevalent phthalate in the environment (Fig. 3). We can see in Figures 2-5 that levels found in the River Hind were particularly high in October and December. This was caused by rehabilitation work involving the digging of the riverbed to create gravel beds for spawning grounds, this disturbance enhancing levels of the more lipophilic compounds which would tend to partition

<table>
<thead>
<tr>
<th>Location*</th>
<th>DEHP (µg/L)</th>
<th>DINP (µg/L)</th>
<th>Dissolved Solids (g/L)</th>
<th>Rainfall (mm)</th>
<th>Temperature (°C)</th>
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</thead>
<tbody>
<tr>
<td>River, Camlin</td>
<td>0.77</td>
<td>0.39</td>
<td>0.269</td>
<td>9.96</td>
<td>11.30</td>
</tr>
<tr>
<td>Lanesborough</td>
<td>1.15</td>
<td>2.07</td>
<td>0.188</td>
<td>10.56</td>
<td>11.40</td>
</tr>
<tr>
<td>River, Hind</td>
<td>0.54</td>
<td>0.45</td>
<td>0.381</td>
<td>10.32</td>
<td>10.70</td>
</tr>
<tr>
<td>Athlone Lock</td>
<td>0.73</td>
<td>0.34</td>
<td>0.218</td>
<td>9.96</td>
<td>11.00</td>
</tr>
<tr>
<td>Shannon Harbour</td>
<td>1.29</td>
<td>1.03</td>
<td>0.347</td>
<td>13.19</td>
<td>11.70</td>
</tr>
<tr>
<td>Banagher</td>
<td>2.74</td>
<td>0.14</td>
<td>0.200</td>
<td>9.82</td>
<td>11.7</td>
</tr>
<tr>
<td>River, Nenagh</td>
<td>2.24</td>
<td>0.85</td>
<td>0.264</td>
<td>9.82</td>
<td>12.20</td>
</tr>
<tr>
<td>Limerick</td>
<td>1.56</td>
<td>0.38</td>
<td>0.117</td>
<td>10.85</td>
<td>12.80</td>
</tr>
</tbody>
</table>

* All sampling sites on the River Shannon unless otherwise stated.
to the sediment. Levels of DINP in the Hind (Fig. 4) for July and August were also elevated, possibly due to low rainfall and low water levels. The levels of phthalates present in the rivers were also dependent on the time of year, rainfall and proximity to sewage effluent or leachate. Conversely, in high rainfall, much higher levels were also found in rivers downstream of such effluents, undoubtedly due to runoff effects. In Lanesborough, Shannon Harbour and Banagher, there were higher levels found in early summer when boating activity was increasing. On comparison with our European counterparts, Martin et al. (2003) determined that DEHP was present in high concentrations in surface waters (0.33-97.8 mg/L). In this study, typical levels found in surface waters (rivers) were between 0.54-11.9 mg/L DEHP. Fatoki & Vernon (UK), (1990) found 25.38 ±10.70 mg/L DBP in river samples tested, which, in their case, were attributed to the presence of a number of polymer factories in the area. By comparison, our values for DEHP and DBP were generally lower than the latter in spite of there being a number of polymer producing companies in the Irish Midlands.

CONCLUSION

The use of SPE along with the narrower bore column created an extremely sensitive method of analysis, allowing for detection of target analytes in the ng/L range, and demonstrated a twenty-fold increase in peak area compared with earlier attempts. The current isocratic method for the determination of phthalates in water and wastewater allows for a stable baseline, hence increasing the sensitivity of the detection method. Pre-concentration of the target analytes on solid phase disks allowed further improvements in detecting low limits of analytes. In this study, environmentally significant quantities of phthalates have been quantified. However, the overall comparison with levels found in pan-European studies showed much lower levels in the River Shannon and its tributaries.

ACKNOWLEDGMENTS

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REFERENCES

THE ANALYSIS OF FRESHWATER RIVERS AS AN ALTERNATIVE SOURCE OF ENERGY IN REMOTE AREAS OF IRELAND

Dr. James Prendergast, Chris O'Donoghue and Gerard Brendan Fitzgerald

ABSTRACT

Hydropower is a well-established method of power generation worldwide. Large-scale hydro (>10MW) is becoming a less attractive option due to socioeconomic reasons. This has led to a renewed interest in small-scale hydropower (<10MW). This paper will raise awareness of small-scale hydropower (SHP) and provide guidelines to developers and small communities who intend on utilising freshwater rivers for electricity production. The last such guide published in Ireland was in 1983. Since then demand for electricity has grown, the electricity market structure has changed, environment protection is of greater importance, turbine and generator technologies have improved and overall the need for renewable electricity generation has increased.

The research will identify the best approach for developing SHP in Ireland. It will compare various river flow assessment techniques and investigate various types of micro-hydro-generators and turbines presently on the market. The environmental aspects of SHP will be discussed and recommendations given on how to minimise the environmental impact of such schemes. A design for an ideal low impact micro-hydropower generation station for two locations in the South West will be presented and an investment analysis will be conducted into the financial viability of micro-hydro power. The paper will show that SHP is a financially feasible, efficient and environmentally friendly sustainable resource.

Key words: renewable energy, hydropower, embedded generation, turbines, generators, environment, financial viability

INTRODUCTION

In order to operate a secure power system it is insufficient to only have an adequate amount of generation. It is also advisable to consider whether an appropriate mix of generation plant types is provided. While the primary function of a generating system is to generate an adequate amount of electricity in accordance with varying customer demand, individual units are needed within the overall generating plant portfolio to fulfil different roles. Some units run all times at rated capacity except for maintenance. These are known as ‘base-load’ generation units. Coal burning plants and combined cycle combustion turbines are most suited to ‘base-load’ operation. During hours of peak demand periods, units may generate electricity for just a few hours to meet the sudden increase. In between ‘base-load’ and ‘peaking’ generation there is a third category of plant operation known as ‘cycling.’ Cycling plants generally operate for ten to twenty hours per day to cater for normal day-time demand. Generation systems such as hydro, pumped storage and open cycle combustion turbines offer high levels of flexibility and are used for peaking and cycling operations (Transmission System Operator, 2005).

As penetration of wind energy levels increase, the requirement for flexible plant will also increase due to the variable nature of wind power. In the current generating plant portfolio the majority of flexible plants (‘cycling’ and ‘peaking’ plants) will be more than 30 years old by the year 2012 (Transmission System Operator, 2005). Therefore, these technologies will become uneconomic as they reach the end of their life-cycles. This will lead the way for new flexible plants to be introduced to the electricity system. It is vital that we now focus on complementing intermittent wind energy with other forms of renewable energy generation. Due to the decentralised nature of renewable energy technologies there is an opportunity for renewable technologies to be developed and connected to the distribution system to ensure a clean, reliable and affordable electricity supply. This is vital to the functioning of a modern economy and society.

EMBEDDED GENERATION

Distributed or embedded generation is expected to become more and more important in future generation systems. There are varying definitions of embedded generation but it can be loosely described as small-scale electricity generation on the distribution network. Central power systems remain crucial to Ireland’s energy supply but their flexibility is limited and costly. Embedded generation complements centralised generation by offering a low capital cost response to peaks in power demand as well as being efficient, reliable and environmentally friendly.

The overall benefits of embedded generation include avoided capital reinforcement of networks, offset energy losses, avoided energy costs due to improved matching of supply and demand, improved security of supply and, of course, lower environmental impacts if renewable generation sources are employed. The major drawback of using more embedded generation on a network is the high grid connection expense to cover the cost of strengthening the network. This may be discouraging to small-scale developers wishing to connect their distributed systems to the grid, but embedded generation and renewable technologies together have the potential to make a large contribution to the increasing environmental, security and demand challenges in Ireland today.

The renewable technologies that have potential of being added to the distribution system as flexible plant are: solid biomass CHP (combined heat and power) facilities, landfill gas, ocean energy and hydropower. Each technology has its distinct market role with unique costs and benefits but it is...
the belief of the authors that hydropower offers the best short to medium term solution. It is a well-developed, mature and highly reliable technology. Hydropower is the most efficient method of producing electricity and it can be well adapted to decentralised electricity production in remote areas of maritime climates. Most importantly, its impact on the environment can be minimal if sufficient precautions are taken.

SMALL-SCALE HYDROPOWER (SHP)

Hydropower in Ireland can be divided into two broad categories: large-scale hydropower facilities, which are plants with an installed capacity of greater than 10MW; and small-scale hydropower, which is less than 10MW. This can be categorised further into mini-hydro (100kW-1MW) and micro-hydro (10kW-100kW). It is unlikely that another large-scale hydropower facility will be built on a 'greenfield' site in Ireland due to planning constraints and the fact that the best sites have already been developed. Therefore, SHP offers the greatest potential. This research is focusing on 'run-of-river' hydropower generation which utilises the flow of a river to generate electricity. Run-of-river systems require little or no damming of the river. This ensures the flow regime is protected at all times. Electricity production with efficiencies of up to 90% can be achieved and SHP facilities enjoy long life-cycles, with plants commonly lasting 50 years or more (Paish, 2002).

HYDROPOWER BASICS

Water pressure is converted into mechanical shaft power through a hydraulic turbine, which is coupled to an electricity generator to produce electricity. The power available at any site is directly proportional to the water pressure (known as the head) and the volumetric flow rate. The gross head is defined as the maximum vertical fall in water between the upstream and downstream levels and it is measured in metres (British Hydropower Association, 2005). The water volume flow passing a particular point on the river at a particular time is measured in cubic metres per second (m³/s). The general formula for the net power output of any hydro scheme is:

\[ P_{Net} = \varepsilon_0 \cdot Q \cdot \sigma \cdot g \cdot H_{gross} \] (Paish, 2002)

where:
- \( P_{Net} \) = the net power output in Watts
- \( \varepsilon_0 \) = the overall efficiency of the system
- \( Q \) = the volume flow rate at that time
- \( \sigma \) = the density of water
- \( g \) = acceleration due to gravity
- \( H_{gross} \) = the gross head

System efficiencies vary from 0.6 to 0.8 due to variations in construction materials, turbine types, generator efficiency, etc. The size of a hydro-turbine depends on the volume of water it has to accommodate. Thus, the generating equipment for a high head, low flow scheme would generally be smaller in size and less expensive than a low head, high flow scheme. We can conclude that the greatest fall over the shortest distance is preferable when choosing a hydro site.

TYPICAL SCHEME LAYOUT

SHP is a very site-specific technology and scheme configurations vary from site to site. Figure 1 shows a river flowing from a high mountainous elevation to a lower level. The flow of water may be regulated by means of a small dam or weir. The weir also slightly raises the water level of the river and diverts sufficient water into the conveyance system. The water is channelled to the forebay tank where it is stored until required and it forms the connection between the channel and the penstock. The penstock carries the water under pressure from the forebay to the turbine. The penstock is a very important part of a hydro project as it can affect the overall cost and capacity of a scheme. The penstock connects to the hydraulic turbine which is located within the powerhouse. There are various types of turbines available and the choice of turbine is dependent on the head and volume of water available. The turbine shaft is either directly or indirectly coupled to a generator and the abstracted water finally returns to natural river channel through the outfall.

RIVER FLOW ASSESSMENT TECHNIQUES

The purpose of hydrologic evaluations is to provide accurate values for stream discharge. The values of stream discharge have to be taken over a long enough period of time to represent the natural flow regime. A minimum record of flow should be available for at least one year and preferably for three years or more (Ackers et al., 1978). Many of Ireland's larger rivers have gauging stations placed along their course, but in most cases there will be no flow records available to a developer when site investigations begin. It is possible to evaluate stream discharge and derive the annual average daily flow at an ungauged river without taking physical, on-site measurements of flow, but these methods are only useful for preliminary surveys. On-site flow measurements are the most accurate and there are four basic techniques for measuring flow in open channels (Ackers et al., 1978). These are: velocity-area methods; dilution techniques; hydraulic structures; and slope-area method.

The velocity-area method utilising the water velocity meter was used (Rantz, 1982) for this research. The dilution and hydraulic structure methods were not used due to their potential environmental impacts (Rantz, 1982).

TURBINES AND GENERATOR EQUIPMENT

Hydraulic turbines can be classified according to the water flow action through the turbine and its structural features. This leads to two main categories of turbine: Action or Impulse turbines and Reaction turbines. Impulse turbines are more efficient at high heads. The original waterwheel is an example of an impulse turbine. A reaction turbine uses

![Figure 1. Typical SHP site layout. (Reproduced with permission from the British Hydropower Association, 2005).](image)
a runner that is completely submerged. The runner blades are profiled so that the pressure difference between inlet and outlet imposes lift forces (Fritz, 1984). This is similar to the reverse action of a boat propeller. Reaction turbines have a slower operating speed and greater efficiency but need a high flow. This makes them more suitable for low head, high flow sites, but both reaction and impulse turbines may be used in micro-hydropower production.

There are three main types of impulse turbine: Pelton, Turgo and the Crossflow (or Banki-Michell). The two main types of reaction turbine are the Francis and the Propeller. A variation of the Propeller turbine is the Kaplan. Shown in Figure 2 are the approximate ranges of head, flow and power output for each of these turbines. Overall, reaction turbines require more sophisticated fabrication than impulse turbines because of the larger and more intricate profiled blades. This leads to increased manufacturing expense but is offset by greater efficiency.

Conversion of mechanical energy into electrical energy is through the use of a generator. Normally only 3-phase alternating current is produced and the two most important types of generator are the Synchronous and the Asynchronous. Synchronous generators are used when the output power is a large portion of the load and they can be used in micro-hydropower production.

Figure 2. Head-flow ranges of hydraulic turbines. (Reproduced with permission from the British Hydropower Association 2005).

In 1985, An Foras Forbartha published a report entitled Small-scale hydro-electric potential of Ireland (An Foras Forbartha et al., 1985). The report provides a significant catalogue of potential small-scale hydropower resource for the Republic of Ireland. A resource table for each county of all the potential sites, with their provisional mean flow and other parameters, is included. The potential installed capacity and the potential annual energy output are both calculated from the provisional mean flow. During the investigation of potential sites listed for Co Kerry, inaccuracies were identified in the resource tables. These inaccuracies have led to a deviation in the calculation of provisional mean flow and hence in the estimated power potential of the particular sites (Fitzgerald, 2006).

SHP POTENTIAL IN IRELAND

In 1997, ALTENER and the ESBI published Total Renewable Energy Resource in Ireland (ALTENER et al., 1997). It concluded that the potential theoretical resource for small hydro-power development in Ireland is approximately 76MW, with an annual energy output of 360GWh. When taking planning, economic and environmental aspects into consideration, the practicable resource is estimated to be 38MW with an annual energy output of 124GWh. However, this data needs to be considered with caution. The 1997 report is based on data in the 1985 report which appears to indicate potential inaccuracies.

DESIGNING A MINI-HYDRO SCHEME

Every hydro site is unique, with approximately 75% of the development cost dependent on location and site conditions. The remaining 25% is relatively fixed on the manufacture of electromechanical equipment (Ramos, 2000). Figure 3 is a flow chart of the main stages required to develop a hydro scheme of less than 0.5MW in Ireland.

The first two phases identify a river suitable for development and estimation of the potential power output. This would be based on a one-day site survey and hydrological records. The pre-feasibility stage identifies three or four design options for scheme layout, possible environmental impacts on local flora and fauna, information on riparian rights, etc. Should one of the options in the pre-feasibility stage appear sensible, a full-feasibility may be commissioned. A detailed hydrologic analysis would be implemented leading to an optimal project design and layout, design of all structures, investigation of potential impact on grid, detailed cost estimate and a financial evaluation. If the proposed scheme is feasible, a connection application is made to ESB Networks, who own the distribution system. Should the application be accepted, the developer will review the design and costs before submitting to the local authority for planning permission. Normally, an Environmental Impact Assessment (EIA) will be requested and a detailed analysis of the scheme design on the river will be carried out. It should be noted that an EIA may take several months, so it is important to choose a site carefully at the project concept stage. Having secured planning permission, the operator will need to secure a Power Purchase Agreement (PPA). A PPA guarantees a purchaser of the electricity over a fixed period. The Renewable energy Feed In Tariff (ReFIT) programme is the latest government support mechanism, and winning hydro contracts would...
be guaranteed 7.2 cent per kilowatt hour for their electricity (O‘Leary et al., 2004).

If financing is secured for the proposed scheme the developer must apply to the CER for licenses. The CER issues three licences: license to construct; license to generate; and license to supply. In this case, a developer would only apply for the first two licenses. This stage of the process is purely legislative to ensure all previous steps have been passed. Only on successful completion of all these stages may construction begin.

**SHP AND THE ENVIRONMENT**

The environmental impacts of hydropower certainly need to be addressed. A hydropower project should fit its environment and not the other way around. It is true to say that EIAs create increased costs to the developer and probably reduced energy production, but by careful planning and careful scheme design it is possible to develop a successful low-profile hydroelectric unit. Such units have been developed in very sensitive areas such as the 500kW scheme built in Snowdonia National Park, Wales.

The impacts an SHP plant can have on its surroundings can be loosely divided into its impacts during construction and impacts during operation. During the construction phase there may be the temporary diversion of the river, use of excavators and trucks for earth moving, and laying of pipelines. The major impacts during operation include the biological impacts to local flora and fauna, landscape, visual and sonic impacts, and recreational impacts. Sonic impacts are not a huge issue with SHP as most powerhouses are located away from residential buildings, but, if necessary, noise levels can be reduced to as low as 70dBA, almost inaudible from outside the powerhouse.

Biological protection is of huge importance when designing an SHP plant. Reserved or compensation flow refers to the minimum flow of water to be maintained at all times in the natural river channel. The Central Fisheries Board recommends a base compensation flow of 12.5% of the long-term mean flow of all rivers, and those with significant angling importance should not be developed (Central Fisheries Board, 2005). If there is fish migration on the river course, then Behavioural Guidance Systems should be used for downstream fish. These are site- and species-specific systems that utilise lights, sound or mechanical devices to divert fish away from the intake. Carefully designed fish ladders should be installed to facilitate the upstream migration of fish.

With regard to SHP plant aesthetics, careful location and design of the powerhouse is necessary for a low impact scheme. Local stone and slate should be used where feasible and, if necessary, an underground powerhouse may be constructed. Penstocks and transmission lines may also be interred. A balance must be maintained between the energy gained from the facility and its impact on the environment.

**SHP AND THE ENVIRONMENT**

Two sites have been identified in Co Kerry which show good potential for development. Flow data was collected at both locations using the FP101 Global Water Flow Probe. The data was analysed using the RETScreen International software package.

Case Study 1 is an old mill site located on the northern side of the Dingle peninsula. The derelict mill is located next to Derrymore River which has no known fish movements; an existing weir structure is in place and the site includes a natural lake at its source. The lake acts as a natural dam and adds to the storage of the site. The technical data is as follows: mean flow = 0.2m³/s; gross head = 96m. This results in an installed capacity of 121kW with an annual energy output of 659MWh. It is predicted that this site would be of low environmental impact and could supply approximately 140 houses with electricity in this area. Table 1 displays the results of the financial analysis for the Derrymore Mill scheme.

In Case Study 1, the redevelopment of Derrymore Mill, the project is a long-term investment with no returns for 25 years. The NPV for the scheme, although a positive value, is only 13% of the initial investment cost. The project is of high risk and investment capital would be

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<td>Initial Design = €52,400</td>
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<td>Turbine &amp; Generator = €128,850</td>
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<td>Connection to D/x system = €40,000</td>
<td>Simple Payback Period = 38 years</td>
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<td>Contingencies = €124,607</td>
<td>Years to positive cash flow = 25 years</td>
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<td>Total Costs = €1,000,283</td>
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Table 1. Financial Summary of Derrymore Mill redevelopment.

Case Study 2: Multi-Purpose Scheme

<table>
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<th>Costs</th>
<th>Financial Summary</th>
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<td>Initial Design = €12,700</td>
<td>Income/year = €12,466</td>
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<td>Civil Works = €136,383</td>
<td>Net Present Value (7.5%) = €133,040</td>
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<td>Turbine &amp; Generator = €44,908</td>
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<td>Connection to D/x system = €28,000</td>
<td>Simple Payback Period = 38 years</td>
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<td>Contingencies = €30,948</td>
<td>Years to positive cash flow = 24 years</td>
</tr>
<tr>
<td>Total Costs = €252,939</td>
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</tr>
</tbody>
</table>

Table 2. Financial Summary of Tonavane Multipurpose water scheme development.
difficult to secure. Further grant aid would be required to redevelop this old mill. The grant aid would largely be directed toward the civil works of the scheme, which at present are in a derelict state.

Case Study 2 is of a river not listed on the 1985 or 1997 reports discussed above. It is a proposed multi-purpose scheme, also located on the northern side of the Dingle peninsula, on the Tonavane River. Located at this site is an existing community water supply scheme for 25 houses. It is proposed that a micro-hydro scheme could be installed at this location. Technical data for the site is: mean flow = 0.1m³/s; gross head = 60m. Considering a large percentage of the flow is maintained for the water supply network, an installed capacity of 24kW with an annual energy output of 240MWh was selected. As most of the existing infrastructure is in place, the proposed scheme would be of low environmental impact and could supply all 25 houses with electricity and water requirements. Table 2 displays the results of the financial analysis for the Tonavane Multipurpose Scheme.

In Case Study 2, the annual income from the scheme is low but as a long-term investment the scheme is attractive. The scheme has the potential to supply 25 homes with water and electricity from the one source. The design of the scheme itself ensures that the quality of the water supply for domestic consumption is unaffected.

It is fair to say that the initial investment costs are high for these schemes but the operation and maintenance costs would be very low and SHP plants have a very long life-cycle. They are located in areas where the potential for large-scale generation from other forms of energy are low and in areas far from the transmission network.

CONCLUSIONS

This paper has attempted to highlight the need for Ireland to diversify its range of electricity generation types and the importance of connecting renewable generation technologies to the distribution network. Small-scale hydropower can fulfil these roles and the energy available is readily predictable. This research has also shown one suitable river that was not included on either the 1985 or 1997 reports. The authors are of the opinion that a new study into hydro resource distribution of rivers that do not have any fish movements along their course, in collaboration with the Central Fisheries Board, should be commissioned. These rivers possess the most potential for future development. Small scale hydropower is a viable source of energy in Ireland, but, for hydro to grow, public acceptance is a very important issue. It must be remembered that each renewable energy technology has its own market role with its own unique costs and benefits but a balance must be maintained between the environment and growing electricity demand.

ACKNOWLEDGMENTS

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REFERENCES


A NEW PROCESS TO IMPROVE THE HEALTHCARE ASPECTS OF HYDROGENATED SUNFLOWER OIL

Shane McArdle, Teresa Curtin and J.J. Leahy

ABSTRACT

A variety of catalysts were tested for the selective hydrogenation of sunflower oil using a variety of heterogeneous catalysts. The reaction was carried out in a batch reactor and the changes in activity and selectivity were periodically monitored during the reaction. Pd and Pt catalysts supported on Al2O3, ZrO2, TiO2, and SiO2 were screened. A range of metal loadings (2-5%) were studied for promotion of selectivity to cis C18:1. The catalysts were compared with a conventional Ni catalyst. The Pd catalysts were found to be much more active than the Ni catalyst. The Pt catalysts were slightly less active than the Pd catalysts which produced much lower trans fatty acids during hydrogenation.

The effect of supports with varying specific area (44-523m2/g) was looked at. It was found that the surface area did not have an effect on the hydrogenation activity. All the catalysts were active over the range of different supports. The surface area had a more obvious effect on trans formation. The results show that the lower the surface area (specifically ZrO2 and TiO2), the higher the level of trans fatty acids formed.

The operating variables (temperature, H2 pressure and agitation rate) proved to have a significant influence on both activity and selectivity. Under the standard operating conditions of high temperature and low pressure, good activity is achieved but a high level of trans fatty acids are formed. Lowering the temperature and increasing the H2 pressure led to lower production of trans fatty acids while maintaining the activity.

Key words: noble metal catalysts, hydrogenation of sunflower oil, trans fatty acids, environmentally friendly

INTRODUCTION

Since its discovery by Wilhelm Normann in 1902, hydrogenation of vegetable oil has become a significant process in the fat and oil industry. The process involves the modification of the liquid oil to a solid or semi-solid product by means of a multi-phase catalytic reaction in the presence of hydrogen (Balakos & Hernandez, 1997). Although the basic process has been used for many years, the reaction is not fully understood; it is very complicated, occurring only under the right set of conditions. Typically, hydrogenation is carried out in a three-phase semi-batch reactor over a porous nickel catalyst at 1-6 bar and around 170°C. The catalyst is suspended in the oil, brought to the required temperature, and the hydrogen is then bubbled through this mixture; this is the start time of the reaction. As the agitator circulates, bubbles of hydrogen gas dissolve in the oil. It then travels to the catalyst surface meeting the unsaturated oil where they react. At present during the hydrogenation process using a batch operation, a quarter of the Ni catalyst is ‘lost’ per run. Each new reaction consists of a mixture of 25% fresh nickel catalyst with 75% of the spent catalyst.

The hydrogenation procedure gives rise to a number of beneficial changes for the oil. The first of these is to increase the stability of the oil against oxidation and decomposition (reactions that affect the flavour of the oil). By partially hydrogenating the oil, its shelf life is also considerably extended. The second reason to hydrogenate is to change the oil’s physical properties such as the melting and solidification characteristics, which is desirable in certain industries such as shortening and confectionary.

Typically, vegetable oils are made up of complex mixtures of triglycerides with fatty acids that have C12-22 atoms that may have 0-3 double bonds on each of the hydrocarbon chains. Figure 1 shows the basic structure of a triglyceride molecule. Fatty acids that contain one or more double bonds distributed along the chain are unsaturated. In the case where there is only one double bond present in the chain it is called monounsaturated or monoenic acid. Conventionally, polyunsaturates contain two or more double bonds found at different positions along the chain. Unsaturation is associated with liquids and lower melting properties. Those fatty acids that have no double bonds are...
known as saturated. They are normally more solid and have higher melting points (Luddy, 1979). During hydrogenation some of the double bonds become saturated while an important proportion of the remaining bonds are isomerised from the naturally occurring cis double bonds to the trans configuration. In recent years there has been growing concern that trans fatty acids are harmful to human health and are linked to increasing the risk of coronary heart diseases (Asherio, 1999). For this reason the need for a process to reduce the formation of trans fatty acids during hydrogenation is required.

The objective of this study entails the development of new catalysts and operating conditions to reduce the formation of trans fatty acids during hydrogenation and to minimise the loss of catalyst. In an attempt to achieve these aims a series of active noble metal catalysts, such as Pt and Pd impregnated on various supports, have been developed that are more active and produce less trans fatty acid than the existing commercial catalyst. Work is being carried out in conjunction with EU partners to support one of the developed catalysts onto a membrane. This novel membrane reactor will have the added benefit of reducing the loss of catalyst during hydrogenation, thereby producing less waste and making it a more environmentally friendly process.

**MATERIALS AND METHODS**

**CATALYSTS PREPARATION**

For this study the main method of catalyst preparation used was wet impregnation. Impregnation of support materials with a catalytically active metal is frequently used when small percentages of active material are required. This technique is centred around the aqueous deposition of an active precursor on a porous support.

The precursor salts used were palladium chloride (PdCl₂, Sigma), hydrogen chloroplatinic acid (H₂PtCl₆.xH₂O, Sigma) and platinum acetyl acetate (Pt(AcAc)₂, Aldrich).

Al₂O₃, ZrO₂ and TiO₂, supplied by Aldrich, were all used to support the metal precursors. The mesoporous silica material (CNS SiO₂) was synthesised according to the procedure by Doyle and Hodnett (Doyle & Hodnett, 2003).

The supported catalysts were synthesised as follows: different weight loadings of Pt and Pd (2-5%) were deposited on the various supports. The required amount of the precursor salt was dissolved in a solvent made up of H₂O:ethanol in a ratio of 1:1. The support was then added to the solution and the mixture was stirred constantly for 16 hours at room temperature. The impregnated catalyst was dried under reduced pressure at 90°C in a rotary evaporator. The resultant solid was dried for a further 2-3 hours at 80°C in an oven. Finally the catalyst was calcined in a furnace at 450°C for five hours in air.

**HYDROGENATION OF SUNFLOWER OIL**

The hydrogenation of sunflower oil (Flora) was carried out under standard conditions using a 600ml Parr pressure reactor, model 4560 (Parr Instrument Co, Moline, Illinois, USA). A typical reaction was run under the following set of operating conditions: 150mg catalyst was reduced in situ by placing the pre-weighted catalyst in the reactor vessel and then passing hydrogen gas over it at 200°C for 2-3 hours. It was then cooled and the system was purged with argon before the sunflower oil (Flora) was introduced (100ml). The temperature of the system was then increased gradually to the desired temperature (100°C or 170°C) and then hydrogen was introduced. The system was agitated using a stirring rate of 400rpm or 600rpm. In all experiments the hydrogen pressure was maintained constant throughout the reaction (3 or 10bar). Oil samples were taken from the reactor every hour over a period of up to five hours.

**OIL ANALYSIS**

Each sample was analysed for its iodine value (IV). The iodine value of an oil or fat is a measure of unsaturation. The test measures the reaction of the double bonds with a halogen, in this case iodine. It is generally expressed in terms of “number of grams of iodine that will react with the double bonds in 100 grams of fats or oils.” A high IV oil contains a greater number of double bonds than a low IV oil. The iodine value of the oil samples in this work were analysed using the standard EN ISO 3961 wijs method (ISO, 1999).

The fatty acid composition of the hydrogenated oils was determined by gas chromatography (GC). The triglycerides were first converted into their fatty acid methyl esters (FAME) following the ISO 5509:2000 method (ISO, 2000). The samples were analysed on a Varian Chromopack CP-3380 GC equipped with a flame ionisation detector using a SP-2560 (100m, 0.25mm ID, 0.2mm film thickness) coated fused silica capillary column (Restek, Bellefonte, PA).

The GC was operated under the following conditions: the oven was...
held at 80°C for four minutes. The temperature was then increased to 240°C at a rate of 4°C/min and held at this temperature for 10 minutes. The carrier gas was helium (B.O.C.) and was maintained at a velocity of 40cm/s through the column with a pressure head of 38Kpa. Sample injections of 1ml were made using a 10ml syringe while the split ratio was 100:1.

CATALYST CHARACTERISATION

The Pt or Pd content of the prepared catalysts was measured by a Varian SpectrAA Atomic Absorption Spectrometer using the required metal cathode lamp. In preparation for analysis the catalyst samples were completely dissolved using a very strong acid such as aqua regia or hydrofluoric acid.

The specific surface area measurements and the pore size distributions of the catalytic materials were measured on a Micrometrics ASAP 2010 system. Nitrogen was used as the adsorbate and the adsorption process was carried out at -196°C. In preparation for analysis, approximately 100mg of sample was out-gassed under vacuum at 200°C for 12 hours.

RESULTS AND DISCUSSION

Palladium and platinum supported catalysts were tested for the hydrogenation of vegetable oil under the same reaction conditions of catalyst concentration (150mg), temperature (170°C), hydrogen pressure (3 bar) and agitation rate (400rpm). The list of catalysts and their principle characteristics are shown in Table 1. The supports used were Al2O3, ZrO2, TiO2 and SiO2 varying in specific area from 44 to 523m2/g. A comparative study of hydrogenation activity was carried out by monitoring the drop in iodine value (IV) with time.

While the platinum supported catalysts were not as active as the Pd, they still showed good activity. The commercial Ni Pricat catalyst presented good activity, but Table 1 shows a much higher metal weight loading of Ni (7.7mg) compared to the Pd and Pt catalysts.

Increasing the metal loading had the beneficial effect of increasing the activity of both the Pd and Pt catalysts. An increase of the Pd metal loading on Al2O3 from 0.89% to 2.14% results in an increased drop in IV over reaction time. After four hours the 0.89%Pd/Al2O3 presented an IV of 82, whereas the 2.14% Pd/Al2O3 drops to an IV of 21 after only three hours – a large increase in activity.

Figure 2 shows the drop in IV over hydrogenation time for the listed catalysts. It can be seen that the Pd supported catalysts (0.89%Pd/Al2O3, 1.71%Pd/ZrO2 and 1.43%Pd/TiO2) show the highest activity per metal weight loading (2.82-4.24) compared to the commercial Ni (1.26) and Pt (1.84-2.71) supported catalysts (Table 1).

Figure 3. Formation of % trans with drop in iodine value for (a) Pd supported catalysts and (b) Pt supported catalysts.

SUPPORT EFFECT

The influence of the support on the catalytic properties was also investigated. Pd and Pt were impregnated on supports of varying surface area as seen in Table 1. The results indicate that the surface area does not really affect the activity of the reaction. All the supported catalysts present very good activity for the hydrogenation reaction, despite the extremely variable specific surface areas, from TiO2 (44m2/g) to SiO2 (523m2/g). Although there is a difference portrayed in the activity results, this is attributed to the varied metal loading on the supports and not the actual support itself.

In terms of formation of trans, the 1.39%Pt/SiO2 presented the lowest level of trans formation. The 1.43%Pd and 1.91%Pt on TiO2 gave rise to the highest level of trans at an IV of 70 (46 and 42%,
conditions on the hydrogenation reaction. Hydrogenation was carried out to investigate the effects of operating conditions. A study was carried out to investigate the effects of operating conditions. Hydrogenation was carried out at a higher temperature (170°C), low H₂ pressure (3bar) and 400rpm, for the same iodine value.

Table 1. List of catalysts and surface characteristic.

<table>
<thead>
<tr>
<th>Catalyst</th>
<th>Support</th>
<th>Actual Metal Loading (%)†</th>
<th>Weight of metal per 150mg (mg)‡</th>
<th>BET surface area (m²/g)</th>
<th>Drop in IVs/mg⁻¹ metal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pd</td>
<td>Al₂O₃</td>
<td>0.89</td>
<td>1.35</td>
<td>127</td>
<td>3.12</td>
</tr>
<tr>
<td>Pd</td>
<td>Al₂O₃</td>
<td>2.14</td>
<td>3.21</td>
<td>124</td>
<td>4.24</td>
</tr>
<tr>
<td>Pd</td>
<td>ZrO₂</td>
<td>1.71</td>
<td>2.56</td>
<td>60</td>
<td>2.92</td>
</tr>
<tr>
<td>Pt</td>
<td>Al₂O₃</td>
<td>1.72</td>
<td>2.58</td>
<td>127</td>
<td>2.48</td>
</tr>
<tr>
<td>Pt</td>
<td>Al₂O₃</td>
<td>3.86</td>
<td>5.79</td>
<td>120</td>
<td>1.84</td>
</tr>
<tr>
<td>Pt</td>
<td>ZrO₂</td>
<td>1.29</td>
<td>1.93</td>
<td>56</td>
<td>2.30</td>
</tr>
<tr>
<td>Pt</td>
<td>TiO₂</td>
<td>1.91</td>
<td>2.86</td>
<td>45</td>
<td>2.71</td>
</tr>
<tr>
<td>Pt</td>
<td>SiO₂</td>
<td>1.39</td>
<td>2.08</td>
<td>523</td>
<td>2.36</td>
</tr>
<tr>
<td>Ni Pricat</td>
<td>-</td>
<td>22</td>
<td>7.7</td>
<td>-</td>
<td>1.26</td>
</tr>
</tbody>
</table>

† Measured by Atomic Adsorption.
‡ Weight of metal per 150mg (concentration of catalyst per reaction), based on the % actual loading measured by AA.

respectively. It seems that the surface area may affect the selectivity of the reaction towards trans formation. The lowest surface area catalysts (TiO₂) gives rise to the highest trans while the highest surface area (SiO₂) forms the lowest level of trans isomers. The ZrO₂ supported catalysts (1.29%Pt and 1.71%Pd), which also have low surface areas (56m²/g), give rise to high levels of trans fatty acids (34-39%), in that order.

EFFECT OF CHANGING OPERATING CONDITIONS

A study was carried out to investigate the effects of operating conditions on the hydrogenation reaction. Hydrogenation was carried out using 1.72%Pt/Al₂O₃ and 1.39%Pt/SiO₂ at a lower temperature and at conditions that would increase hydrogen coverage of the catalysts surface: 100°C, 10bar H₂ pressure and 600rpm (Niklasson, 1987; Nohair, 2004).

Figures 4a and b show the reaction profiles for the catalysts. Under these conditions the activity of the 1.71%Pt/Al₂O₃ catalyst was significantly decreased, requiring four hours to reach an IV of 80 whereas only two hours were required to reach an IV of 80 under the high temperature (170°C) and low pressure conditions (3bar). This relatively slow rate of reaction is clearly demonstrated by the slow consumption of the linoleate (C18:2). However, these new reaction conditions had a beneficial effect on the selectivity, forming only 10.8% trans after this time was 26%.

A similar comparison for 1.39%Pt/SiO₂ catalyst is shown in Figure 4b. An iodine value of 70 (represented by the vertical dashed line in the figure) was achieved after two hours for the 1.39%Pt/SiO₂ operated at 100°C, 600rpm and 10bar.

The corresponding trans content was 10.2%. When hydrogenation was carried out at a higher temperature (170°C), low H₂ pressure (3bar) and 400rpm, an iodine value of 70 was achieved after four hours reaction. In addition, the trans content after this time was 26%. Therefore, a significant improvement in terms of both activity and trans inhibition was achieved at low temperature and high pressure conditions.

The drop in % trans for both the catalysts can be attributed to the change in reaction conditions. Under the high pressure and low temperature variables, the activity for the Al₂O₃ supported catalyst is reduced (low temperature, low activation energy) whereas the SiO₂ catalyst activity is increased. It seems that the large surface area of the SiO₂ coupled with its large pores facilitates a better mass transfer of H₂ on the surface of the catalyst, allowing for better activity (Plourde, 2004).

CONCLUSION

From this study it is clear that the Pt supported catalysts were very active and formed less trans isomers than the corresponding Pd and the commercial Ni Pricat catalysts. While the Pd catalysts showed the highest activity based on the actual metal content, they formed the highest level of trans.

The Pt supported on mesoporous silica catalysts gave rise to the desired mix of selectivity and activity (good activity and low trans formation) of all the catalysts tested.

Operating conditions were also found to be an important variable in achieving optimum selectivity and activity. Operating under low temperature (100°C) and high pressures (10bar) favours less trans formation while maintaining overall activity.

ACKNOWLEDGMENTS

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REFERENCES


PROCESS TO IMPROVE HEALTHCARE ASPECTS OF HYDROGENATED SUNFLOWER OIL
THE CONTRIBUTION OF THE Q METHOD TO BOTTOM-UP SCENARIO ANALYSIS

Pauline Ryan, Bernadette O’Regan and Richard Moles

ABSTRACT

Alternative pathways of household material (energy, transport, water, etc) consumption are necessary in pursuing more sustainable development in settlements. Current patterns are contributing to environmental decline due to unsustainable rates of natural resource extraction and compromising of the environmental sink function. Identifying the factors shaping household consumption will contribute to constructing plausible scenarios for alternative consumption patterns. This process will also identify the motivations required by householders to alter their current trends and adopt more sustainable consumption pathways. The Q method was selected to provide an insight into the factors influencing the consumption patterns. The predominantly social science methodology of Q demonstrated its ability to structure the subjectivities of participants to better inform scenario planning. The results indicated that attitudes towards consumption behaviour are motivated by a diversity of factors. There was a consensus among the three discourses that individuals have a responsibility to adapt their lifestyles to practice environmentally sound consumption. However, the needs of the community, technological advances, government leadership and financial factors may influence the degree to which householders will adapt to more sustainable consumption patterns. The implications of this analysis are such that, even within a small settlement, there is the likelihood of disparity of attitudes governing consumption. Using Q to expose these attitudes has the potential to better inform and formulate acceptable scenarios and subsequent policy recommendations for sustainable development.

Key words: sustainability, scenarios, Q method

INTRODUCTION

A keyword in the definition of scenario, as it applies to sustainability science, is plausibility (Schreider & Mostovaia, 2001; Shiftan et al., 2003; Swart et al., 2004). A plausible scenario for sustainable development is one that incorporates existing practices and knowledge of the system being examined (Schreider & Mostovaia, 2001; Swart et al., 2004). Unsustainable materials consumption is one of the chief obstacles to sustainable development (Spangenberg & Lorek, 2002). Sustaining society’s consumption patterns through natural resource extraction and manipulation has resulted in environmental depletion and degradation (Barrera-Roldan & Saldivar-Valdes, 2002). Better management of, and reduction of, materials consumption may thus effectively operationalise the demands of sustainable development (Spangenberg & Lorek, 2002; Hinterberger et al., 1997). Scenarios to identify pathways to reduce or better manage materials consumption will benefit from involving the stakeholders towards whom the scenarios are targeted (Swart et al., 2004).

The Q method is described as a “technique for the objective study of human subjectivity” (Brown et al., 1999). Developed in the 1930s, its underlying assumption is that of the finite diversity of discourses (Barry & Proops, 1999). Discourses refer to viewpoints or opinions held by individuals on a particular topic and are subject to their circumstances at time of extraction (Barry & Proops, 1999). Q method offers a means with which to extract “social discourses,” seeking commonality among the discourses of individuals (Brown et al., 1999; Barry & Proops, 1999). Its emphasis is on what views individuals hold, rather than concerning itself with which individuals hold which views. Traditional survey methods (referred to as R methodologies) seek to understand why individuals hold certain views, and what are the traits (such as age, gender, income, etc) that influence their views (Barry & Proops, 2000). Barry and Proops (2000) provide a comprehensive account of the differences of Q and R methodologies. However, the following concisely summarises the differences: “In summary, in R methodology pre-defined attitudes are explained by individual characteristics … Q seeks to uncover latent discourses and understand the degree to which individuals subscribe to these” (Barry & Proops, 2000).

The discourses surrounding the materials consumption of households were examined in the case study settlement of Freshford, Co Kilkenny (population 756; CSO, 2003). Located in the southeast of Ireland, Freshford is one of more than 550 small settlements in Ireland with populations under 1,500. Small settlements contribute to approximately 10% of Ireland’s overall population and the role that these settlements can play in the future sustainable development of the country is one that will be examined by this research. Earlier research in the settlement has examined the baseline of consumption for the categories of energy, food, housing, transport, waste and water. The ecological footprint (EF) of the consumption data was calculated and used as an indicator of environmental sustainability. The EF will also be used to indicate the sustainability of alternative consumption pathways in the scenarios, and for this reason the EF driving forces were included in the Q method. The aim of this study was to identify the attitudes and motivations underpinning householders’ present and potentially future consumption patterns and, in turn, outline how the Q method can contribute to constructing bottom-up plausible scenarios for more sustainable settlement consumption.

MATERIALS AND METHODS

The Q method was applied in this research to gain insight into the positions and preferences shaping householders’ materials consumption.
The following steps are involved in its application:

- Q sample
- Q sort
- Factor analysis and rotation
- Factor interpretation

**Q SAMPLE**

The Q sample refers to a set of statements presented to study participants for sorting. The number of statements comprising a Q sample ranges in the literature from 64 to 33, with 36 considered optimal for both researcher and sorter (Dryzek & Berejikian, 1993; Barry & Proops, 1999; Swedeen, 2005). This study generated 33 statements for sorting by Freshford residents. The statements were generated, and constrained, using the household driving forces of the EF. To clarify, the EF driving forces were considered those parameters of the EF calculation that a householder was deemed capable of influencing by virtue of choice, thus impacting on the EF total for that category. An example of the process is provided for the transport statements (see Table 1 and Table 2). Certain assumptions were made to generate the statements: these assumptions were based on alterations possible to household consumption patterns. Each statement can be related to an EF driving force and the subsequent assumption regarding driving force alteration. This method was applied to all categories of household material consumption.

**Q SORT**

The ranking of statements by Q participants is referred to as Q sorting. The participants were asked to rank the statements on a scale of those statements that they “agreed with most strongly” (+3) to “disagreed with most strongly” (-3). Forced distribution of a pyramidal nature is used in Q method. This facilitates the ranking of one statement against another: the intensity of the method ensures low numbers of participants can meaningfully provide significant data (Barry & Proops, 1999). The ranking applied in this research is displayed in Figure 1.

**FACTOR ANALYSIS AND ROTATION**

PCQWin software was used to carry out the statistical analysis of the individual Q sorts. The first stage of the analysis conducted a correlation matrix of the Q sorts. This correlation matrix was subjected to the factor analysis statistical technique to further explain the pattern of correlations among the Q sorts or variables. This assists in identifying and extracting a small number of factors that explain most of the variance present in the larger number of variables. This method uses tests such as principal component analysis, unweighted least squares method and, in the case, of PCQWin, the centroid factor analysis method. The loading of individual Q sorts to each of the factors is assessed at significance level p<0.01. This is a default setting within the PCQWin software and is calculated using a multiplier (2.58 for p<0.01) divided by the square root of the number of statements (Exel & Graff, 2005). Factor eigenvalues (the sum of the squares of the factor loadings) were calculated for each of the extracted original factors to anticipate the number of factors that will emerge in the final set. Only significant (eigenvalues <1.00) factors were rotated (van Exel & de Graff, 2005). Rotation using the varimax statistical test repackages the data as ideal Q sorts, a best fit for the expression of views for each of the significant factors (Barry & Proops, 1999).

**Table 1. The driving forces of the ecological footprint of transport and the factors that can alter it.**

<table>
<thead>
<tr>
<th>Driving Force</th>
<th>Alteration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Car kilometres</td>
<td>(a) Distances travelled (b) Location of services</td>
</tr>
<tr>
<td>Car occupancy</td>
<td>(a) Increase or decrease the occupancy of private or public transport</td>
</tr>
<tr>
<td>Fuel CO₂ emissions</td>
<td>(a) Type of fuel (b) Vehicle engine size</td>
</tr>
<tr>
<td>Road share</td>
<td>(a) Choice of travel mode</td>
</tr>
</tbody>
</table>

**Table 2. The transport statements used in the Q study of Freshford and the interlinkages with driving force alteration highlighted.**

<table>
<thead>
<tr>
<th>Statement</th>
<th>Cross-reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>(6) ‘The shops in Freshford are not capable of satisfying my household’s weekly shopping requirements’</td>
<td>1a &amp; 1b</td>
</tr>
<tr>
<td>(9) ‘Household members prefer to drive their own car; car sharing (to example: work) is not convenient’</td>
<td>2a</td>
</tr>
<tr>
<td>(12) ‘Public transport in Freshford is adequate for the needs of the community, and does not require improvement’</td>
<td>4a</td>
</tr>
<tr>
<td>(15) ‘Employment sources in Freshford are not adequate to support the current population’</td>
<td>1a &amp; 1b</td>
</tr>
<tr>
<td>(17) ‘The environment does not influence my selection of car engine size’</td>
<td>3b</td>
</tr>
<tr>
<td>(24) ‘There are adequate recreational facilities located in the village for community members’</td>
<td>1a &amp; 1b</td>
</tr>
<tr>
<td>(25) ‘My household would not consider using a vehicle run on alternative fuels, such as ethanol or electricity’</td>
<td>3a</td>
</tr>
<tr>
<td>(29) ‘A rail network should be developed in and around Freshford to facilitate travel requirements to services such as work, shopping, education and recreation’</td>
<td>4a</td>
</tr>
</tbody>
</table>

**Figure 1. Pyramidal structure of the Q sort answer sheet.**
FACTOR INTERPRETATION

The purpose of Q method is to extract and describe the shared viewpoints of sorters. Factor interpretation used the factor scores of the statements (see Table 3). The factor scores received after factor analysis and rotation reflect a mindset among the individuals that participated (Brown, 1980). The process of interpreting the ideal Q sorts is described as more art than science, but it does remain guided and constrained by the factor scores (Brown et al., 1999). The interpreted factors are a reflection of the sorters’ shared attitudes and viewpoints towards the statements.

“Those concerned that investigator bias will exercise undue influence over results fail to appreciate the central role of the Q sorter, whose own subjective understanding is at the centre of the enterprise. Statements in a Q sample are not assumed to carry meaning a priori ... rather, the Q sorter projects meaning onto the statement, a posteriori” (Brown et al., 1999).

RESULTS

Twenty individual Q sorts produced three distinguishing factors or social discourses. The factor scores were used to interpret each of the discourses (see Table 3). In addition to Q sorting, participants were also asked to comment on the reasons for selecting their distinguishing +3 and -3 statements. These comments were used to aid interpretation.

There was agreement among all three discourses that the actions of the individual have an important role to play in environmental protection (Statement # 19: A: 2, B: 2, C: 3). There was also widespread agreement that individuals have a responsibility to create less waste (Statement # 5: 3, 3, 3). The opportunity to consume renewable electricity would be welcomed by all discourses (Statement # 11: 2, 2, 2).

DISCOURSE A

Influenced by: Needs of the community

The noteworthy agreement (+3, +2) statements for this discourse were: 5, 15, 26, 6, 7, 11, 19. The noteworthy disagreement (-3, -2) statements were: 4, 8, 31, 3, 23, 24, 27 (see Table 3). This discourse agreed that environmental protection is influenced by individual actions and did not agree that responsibility lies solely with government: “I believe the government is doing a lot, but it is up to us all, ourselves, to help protect our one and only environment” and “environmental responsibility is not just the government’s responsibility, it is up to the person to sort out their own rubbish.” Individuals have a responsibility to create less waste, but did not agree that increasing wastes costs can help achieve this: “If you increase [costs], people will dump more on the side of the road.” and “I think that it is up to everybody to try and create less waste as it is getting to be a major problem getting rid of waste.” Composting and recycling were highlighted as convenient methods of reducing waste production: “If we could try and recycle just 5% extra every year, in twenty years we would have no more waste. I know 100% recycling is impossible but how close we get is up to ourselves. We owe it to our kids.” This discourse expressed strong agreement with the inadequacies of services in the settlement. Employment, shopping and recreational facilities are not sufficient to service the settlement population: “Freshford village needs a supermarket, drapery shop and others ... hardly any employment in Freshford. People have to drive to Dublin everyday for employment.” The consumption of renewable energy was agreed by this discourse to be a requirement for the future of the settlement. Such a renewable source could be community driven, as this “would make more sense.” Changes to the household heating system would be acceptable to this discourse. Not only would it welcome a renewable energy source, but also natural gas may be acceptable in the transition to renewable energy as “gas is much cleaner.” This discourse also agreed with the use of eco-friendly materials in house building, while ensuring that the materials used contribute to long building lifespan: “Cut down on eco-destroying things wherever we can,” and “Eco-friendly houses will improve the environment greatly.”

DISCOURSE B

Influenced by: Technology and Government

The noteworthy agreement statements for this discourse were: 1, 5, 23, 11, 13, 19, 26. The important disagreement statements were: 25, 27, 31, 8, 12, 20, 30. The importance of individual actions to help the environment and create less waste was also prominent in this discourse. Recyclable packaging is purchased where possible, and, similarly to Discourse A, recycling and composting were agreed to be convenient methods of waste disposal: “It’s crazy the amount of packaging in some goods, just not necessary,” and “Composting is simple.” This discourse was not against increasing the costs of waste disposal to encourage waste reduction, although weak agreement was expressed (-3, 1, -3). It expressed the view that individual actions alone are not sufficient in protecting the environment. The environmental responsibilities of government were highlighted: “Government has signed up to Agenda 21 and Kyoto Agreement,” and “Government has to show leadership.” This discourse agreed that technology is important in reducing negative environmental impact (1, 3, 0). It would welcome the use of eco-friendly technology in building: “The technology is there, so why not use it for new houses?” and to reduce waste: “All kinds of new technology are becoming available for manufacturing and recycling.” In addition, the technology to adapt to alternative vehicle fuels would be acceptable: “Seriously considering bio-diesel, both to grow and use.” This discourse was unique in its positioning of a food consumption statement among the extreme statements. It agreed that reducing meat consumption may play a part in reducing environmental impact considering that “in areas of the world, forests are turned into grazing land for cattle.” The standards of services in the settlement were deemed adequate by this discourse (shopping: 2, -1, 0), (recreation: -2, 0, -2), (employment: 3, -1, 2). However, an improvement in public transport to access these services is required: “Buses could be run more frequently” for car sharing is not always convenient (0, 1, -2) as “people live over a wide area and work different hours, so car sharing is not usually workable.”

DISCOURSE C

Influenced by: Economic factors

The important agreement statements for this discourse were: 5, 7, 19, 3, 11, 13, 15. The noteworthy disagreement statements were: 4, 12, 21, 9, 24, 28, 32. This discourse also highlighted the important role of the individual. Individuals should seek recyclable packaging where possible; however, there was also agreement that recycling can make dealing with household waste more difficult (-3, -3, 1). Increasing wastes cost will not help to reduce waste for “waste costs are high enough, so shouldn’t be increased, plus it would make people not bother with recycling any more,” and “it’s the high cost that makes people burn in the backyard or fireplaces.” A renewable source of electricity would be acceptable for use in the home as “a household would be helping the world if we used renewable materials for electricity.” Solid-fuelled open fires are a necessity for this discourse (1, 1, -3). However, increasing costs of fossil fuels would impact on this discourse’s level of fuel use: “While I agree that we need to be
more aware of our environment and the damage, which could be
lessened, economic features play an important role in how far each
household may contribute to saving our environment … life and its
economic costs sometimes erode away our good intentions. It is more
important to keep a roof over my family’s head than worry about
economic costs sometimes erode away our good intentions. It is more
household may contribute to saving our environment … life and its
lessened, economic features play an important role in how far each
household may contribute to saving our environment … life and its

7. Materials that contribute to a long building lifespan should be used when building a house
2.0
8. A community scheme for renewable heating and power is not a requirement for the future of Freshford
2.0
9. Household members prefer to drive their own car, car sharing (to example: work) is not convenient
0.1
10. Landfilling of waste is a satisfactory waste disposal method for our household waste
1.0
11. My household would prefer to use electricity generated using renewable materials
2.2
12. Public transport in Freshford is adequate for the needs of the community and does not require improvement
-1.2
13. I make sure that the packaging of my purchases is recyclable where possible
1.2
14. In the future people are going to have to lower their material standards of living due to resource shortages and other environmental pressures
0.1
15. Employment sources in Freshford are not adequate to support the current population
3.2
16. My household has sufficient energy efficient measures (such as roof, wall insulation etc) and does not require improvement
-1.1
17. The environment does not influence my selection of car engine size
-1.0
18. Increased numbers of flats or apartments would be acceptable in the community as smaller houses have less impact on the environment
1.1
19. Individual actions taken by householders can help the environment
2.2
20. Reducing the amount of meat in my diet would not benefit the environment
0.2
21. Open fires in households are not a necessity, rather a luxury
1.1
22. Reducing water consumption is not a household priority
0.1
23. Environmental protection is the responsibility of Government
-1.3
24. There are adequate recreational facilities located in the village for community members
-2.0
25. My household would not consider using a vehicle run on alternative fuels such as ethanol or electricity
-1.3
26. New houses should be built using all available eco-friendly technology
2.3
27. Composting is not a convenient means of reducing waste
-2.3
28. Potential increasing costs of fossil fuels will not affect my household’s level of use (these include oil, coal, turf, etc)
-1.0
29. A rail network should be developed in and around Freshford to facilitate travel requirements to services such as work, shopping, education and recreation
1.1
30. The source (whether Irish or international) of building materials is not an important consideration when building a house
0.2
31. Recycling makes dealing with household waste disposal more difficult
-3.3
32. There is less water wasted in a household with a large number of occupants
0.0
33. Reducing the amount of food eaten in my household would not benefit the environment
0.0

Table 3. Q Method results for Freshford and the distinguishing discourse scores.

<table>
<thead>
<tr>
<th>Statements</th>
<th>A</th>
<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Technology is capable of reducing negative environmental impact</td>
<td>1</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>2. My household always purchases organic food products where possible</td>
<td>-1</td>
<td>0</td>
<td>-1</td>
</tr>
<tr>
<td>3. My household would not prefer to use natural gas, and no change to our current household heating fuels is necessary</td>
<td>-2</td>
<td>-1</td>
<td>2</td>
</tr>
<tr>
<td>4. Waste costs should be increased to encourage less waste creation in households</td>
<td>-3</td>
<td>1</td>
<td>-3</td>
</tr>
<tr>
<td>5. Individuals have a responsibility to create less waste</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>6. The shops in Freshford are not capable of satisfying my household’s weekly shopping requirements</td>
<td>2</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>7. Materials that contribute to a long building lifespan should be used when building a house</td>
<td>2</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td>8. A community scheme for renewable heating and power is not a requirement for the future of Freshford</td>
<td>-3</td>
<td>-2</td>
<td>0</td>
</tr>
<tr>
<td>9. Household members prefer to drive their own car, car sharing (to example: work) is not convenient</td>
<td>0</td>
<td>1</td>
<td>-2</td>
</tr>
<tr>
<td>10. Landfilling of waste is a satisfactory waste disposal method for our household waste</td>
<td>1</td>
<td>-1</td>
<td>-1</td>
</tr>
<tr>
<td>11. My household would prefer to use electricity generated using renewable materials</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>12. Public transport in Freshford is adequate for the needs of the community and does not require improvement</td>
<td>-1</td>
<td>2</td>
<td>-3</td>
</tr>
<tr>
<td>13. I make sure that the packaging of my purchases is recyclable where possible</td>
<td>1</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>14. In the future people are going to have to lower their material standards of living due to resource shortages and other environmental pressures</td>
<td>0</td>
<td>-1</td>
<td>1</td>
</tr>
<tr>
<td>15. Employment sources in Freshford are not adequate to support the current population</td>
<td>3</td>
<td>-1</td>
<td>2</td>
</tr>
<tr>
<td>16. My household has sufficient energy efficient measures (such as roof, wall insulation etc) and does not require improvement</td>
<td>-1</td>
<td>1</td>
<td>-1</td>
</tr>
<tr>
<td>17. The environment does not influence my selection of car engine size</td>
<td>-1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>18. Increased numbers of flats or apartments would be acceptable in the community as smaller houses have less impact on the environment</td>
<td>1</td>
<td>1</td>
<td>-1</td>
</tr>
<tr>
<td>19. Individual actions taken by householders can help the environment</td>
<td>2</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>20. Reducing the amount of meat in my diet would not benefit the environment</td>
<td>0</td>
<td>-2</td>
<td>1</td>
</tr>
<tr>
<td>21. Open fires in households are not a necessity, rather a luxury</td>
<td>1</td>
<td>1</td>
<td>-3</td>
</tr>
<tr>
<td>22. Reducing water consumption is not a household priority</td>
<td>0</td>
<td>-1</td>
<td>-1</td>
</tr>
<tr>
<td>23. Environmental protection is the responsibility of Government</td>
<td>-2</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>24. There are adequate recreational facilities located in the village for community members</td>
<td>-2</td>
<td>0</td>
<td>-2</td>
</tr>
<tr>
<td>25. My household would not consider using a vehicle run on alternative fuels such as ethanol or electricity</td>
<td>-1</td>
<td>-3</td>
<td>0</td>
</tr>
<tr>
<td>26. New houses should be built using all available eco-friendly technology</td>
<td>3</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>27. Composting is not a convenient means of reducing waste</td>
<td>-2</td>
<td>-3</td>
<td>-1</td>
</tr>
<tr>
<td>28. Potential increasing costs of fossil fuels will not affect my household’s level of use (these include oil, coal, turf, etc)</td>
<td>-1</td>
<td>0</td>
<td>-2</td>
</tr>
<tr>
<td>29. A rail network should be developed in and around Freshford to facilitate travel requirements to services such as work, shopping, education and recreation</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>30. The source (whether Irish or international) of building materials is not an important consideration when building a house</td>
<td>0</td>
<td>-2</td>
<td>0</td>
</tr>
<tr>
<td>31. Recycling makes dealing with household waste disposal more difficult</td>
<td>-3</td>
<td>-3</td>
<td>1</td>
</tr>
<tr>
<td>32. There is less water wasted in a household with a large number of occupants</td>
<td>0</td>
<td>0</td>
<td>-2</td>
</tr>
<tr>
<td>33. Reducing the amount of food eaten in my household would not benefit the environment</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

DISCUSSION

The application of the Q method in this study has demonstrated its ability to provide insight into the factors influencing the consumption patterns of the relevant participants. The importance of this is such that the trend prevalent among scenario builders to use unsupported guesses regarding the drivers of lifestyle change can be avoided (Michaelis, 2003). This will contribute to designing better policies for more sustainable development and enable policy-makers to make better use of their resources (Bin & Dowlatbadi, 2005). Householders, as
The ensuing phase of scenarios construction for sustainable consumption pathways for the settlement will involve individual and collective consideration of the discourses. Furthermore, these three discourses may be indicative of viewpoints that prevail among a wider population. Maintaining the link with EF throughout the application of the Q method will enable the sustainability of the constructed scenarios to be assessed. The results underlined that individuals’ willingness to adapt to more sustainable practices is motivated by a number of issues. The implications of this analysis are such that, even within a small settlement, there is the likelihood of disparity of attitudes. This realisation and the use of Q to uncover these attitudes has the potential to better inform and formulate acceptable scenarios and subsequent policy recommendations for sustainable development.

ACKNOWLEDGMENTS

I would like to acknowledge the “Q” assistance of Paul Kearney, Donnacha Doody, John Barry and Clive Robinson.

REFERENCES


IMPACT ASSESSMENT OF HIGHWAY DRAINAGE ON SURFACE WATER QUALITY

Mesfin B. Desta and Michael Bruen

ABSTRACT

Runoff from roads (mainly motorways and dual carriageways) has been identified as a potential source of contaminants (heavy metals and hydrocarbons) that may impair the beneficial use of receiving waters and the biota living in them. This study was conducted to determine whether or not road runoff had any impact on receiving streams under the current drainage design and maintenance practice in Ireland. Over 50 streams receiving runoff from major Irish roads were surveyed and 14 of them were selected for detailed monitoring. Water and sediment samples were collected from upstream and downstream locations of each drainage outfall to see if there is any increase in concentrations at the downstream sites. Additional samples were collected from streams that are not directly connected to road drainage, which were regarded as control sites. All samples were analysed for heavy metals (Cd, Cu, Pb, and Zn) and 16 US EPA specified polycyclic aromatic hydrocarbons (PAHs). Heavy metal concentrations in the stream sediment did not show any statistically significant increase at the downstream sites except in some streams (Doonfin, Slane and Rowanstown) for some metals. PAHs have, however, showed significant increases in two of the monitored streams (Owendoher and Glenview). Road runoff appears to have some impact on the quality of receiving water if discharged without treatment.

Key words: heavy metals, PAHs, highway runoff, receiving water, impact assessment

INTRODUCTION

Runoff from motorways and dual carriageways may contain significant loads of heavy metals, hydrocarbons, nutrients and other toxic substances, which may affect the quality of receiving waters. These pollutants are predominantly in or associated with the particulate phase of the runoff (Roger et al., 1998) and tend to accumulate in receiving-water sediments. Sediment contaminated by road runoff has been shown to be toxic to freshwater organisms (Malby et al., 1995; Boxall & Maltby, 1997) or to be a source of contaminants that may result in excessive bioaccumulation (Goodyear & McNeill, 1999). Of particular interest are Polycyclic Aromatic Hydrocarbons and the free metal ions of Cd, Cu, Pb and Zn, which are immediately toxic to biota at low concentrations and are only slowly detoxified by chemical transformations.

Studies on road-deposited sediment showed that these pollutants are derived mainly from human activities (Sutherland et al., 2001), the main sources being the wear and tear of vehicular parts and exhaust emissions. For example, tyre wear is a source of Zn and Cd; brake wear is a source of Cu, Pb, Cr and Mn, and engine wear and fluid leakages are sources of Al, Cu, Ni and Cr (Sansalone et al., 1996; Legret & Pagotto, 1999). PAHs are products of the incomplete combustion of oils and fuels. When released directly into the atmosphere through burning, lower molecular weight PAHs are generally dispersed much more quickly than those of higher molecular weight ones before they return to the road or surrounding land directly or in rainfall. PAHs enter water directly from the air with dust and precipitation, or particles washed from the road surface by runoff. Most PAHs do not dissolve easily in water but lower molecular weight PAHs are more water-soluble than the higher molecular weight PAHs. PAHs are slow to degrade in the environment, and sediments in particular are sinks where these chemicals tend to concentrate.

Studying the pollutant concentration in river sediment has been used to determine the impact of pollution sources on receiving waters more reliably than just water samples because sediment characteristics are less variable over time and reflect the long-term effects of pollution sources (Förstner, 2004). Maltby et al. (1995) and Perdikaki & Mason (1999) compared upstream and downstream trace metal concentrations in the sediments of rivers crossed by motorways to assess the impact of road runoff on the receiving water quality. Their work inspired the investigation reported here, whose objective is to determine the impact of road runoff on receiving-water quality using water and sediment samples taken upstream and downstream of motorway and dual carriageway crossings in Ireland.

MATERIALS AND METHODS

THE SAMPLING SITES

More than 50 streams receiving road runoff from major Irish roads were surveyed for suitability of water and sediment sampling. Fourteen sites were finally selected for detailed monitoring (Table 1 and Figure 1). These sites were selected because they were easily accessed for sampling and were free from drainage of other sources of pollution such as farmyards, etc. Smaller streams were preferred to larger ones since they have lower dilution capacity and allow measurement of differences in concentrations. Each site was sampled from upstream and downstream locations of highway drainage discharge points. Additional samples were collected from sites with relatively low traffic volume or streams not connected to road runoff to serve as controls for the measurement.

SAMPLING AND SAMPLE PREPARATION

Samples were collected in 2002/2003 (1st Test) and 2005 (2nd Test). The sampling program in 2005 was designed to include more pristine sites and revisit some of the sites
sampled previously to establish temporal variation in the determinands, if it exists. At each site, sediment samples were collected from three locations on the upstream and downstream sides of the road crossing. The downstream samples were collected beginning from adjacent to the drainage outfall and further downstream 30 to 40 metres apart. The upstream samples were similarly collected from upstream of the road drainage discharge point at similar distances as the downstream side. The top 2-5cm of the sediment was collected at each station using scoops (plastic for heavy metals and stainless steel for PAHs) and transferred to pre-labelled clean plastic bags for heavy metals analysis and amber glass bottles for PAHs analysis. Samples were stored in a refrigerator until analysis.

Water samples were also collected at the same time but prior to sediment collection to avoid effects on the water of resuspension during sediment sampling.

**ANALYSIS**

The procedure for extracting metals from sediment is based on that of Sriyaraj *et al.* (2001) and Part 3030E of the standard methods (APHA, 1998). Sediment samples were oven-dried at 103-105°C for 24 hours and cooled in a desiccator. The dried samples were ground and sieved to a fraction size of ≤250mm. Exactly 2.0g of each sample was transferred into a beaker and approximately 50mL of distilled water was added. Five millilitre of conc. HNO₃ (69%, w/w) was then added and allowed to stand overnight. The mixture was evaporated on a hot plate to a volume of 10 to 20mL. The samples were then filtered.
through Whatman 934-AH Glass Microfibre Filter. The filtrates were made up to 100mL with distilled water and stored in acid-rinsed plastic containers. Duplicates of each sample and blanks subjected to the same process were included each time the analysis was done.

The metal determination of the solution was carried out by Atomic Absorption Spectrometry in accordance with Part 3111B of APHA (1998). Samples were analysed for Cd, Cu, Pb and Zn. The working standard solutions were 2, 1 and 0.1mg/L from a stock solution of 1000mg/L.

Water samples were analysed for total alkalinity, BOD5, non-purgeable organic carbon (NPOC), nitrate + nitrite, and total phosphate. All parameters were analysed in compliance with the standard methods of the APHA (1998). In situ measurements of pH, DO, specific conductivity and temperature were also taken.

Sediment samples were sent out to ALcontrol Laboratories for PAHs analysis.

RESULTS

WATER QUALITY

There was no significant difference between concentration levels prevailing at the upstream and downstream sites (Table 2). Neither was there any significant difference between the two testing periods.

Table 2. Average concentrations of determinands at the two sampling periods.

<table>
<thead>
<tr>
<th>Site</th>
<th>Total Alkalinity, mg/L CaCO₃</th>
<th>NPOC, mg/L</th>
<th>Nitrate + Nitrite as N, mg/L</th>
<th>Total PO₄-P, mg/Lx10⁻³</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1st Test</td>
<td>2nd Test</td>
<td>1st Test</td>
<td>2nd Test</td>
</tr>
<tr>
<td>Slane US</td>
<td>131</td>
<td>257</td>
<td>2.9</td>
<td>2.2</td>
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<tr>
<td></td>
<td>140</td>
<td>259</td>
<td>2.8</td>
<td>2.3</td>
</tr>
<tr>
<td>Slane DS</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hartwell US</td>
<td>221</td>
<td>285</td>
<td>1.8</td>
<td>2.1</td>
</tr>
<tr>
<td></td>
<td>215</td>
<td>280</td>
<td>1.3</td>
<td>2.1</td>
</tr>
<tr>
<td>Hartwell DS</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rowanstown US</td>
<td>317</td>
<td>357</td>
<td>2.9</td>
<td>3.2</td>
</tr>
<tr>
<td></td>
<td>323</td>
<td>357</td>
<td>2.9</td>
<td>1.5</td>
</tr>
<tr>
<td>Rowanstown DS</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lyreen US</td>
<td>281</td>
<td>355</td>
<td>4.6</td>
<td>4.0</td>
</tr>
<tr>
<td></td>
<td>274</td>
<td>353</td>
<td>4.7</td>
<td>4.1</td>
</tr>
<tr>
<td>Lyreen DS</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>White US</td>
<td>255</td>
<td>166</td>
<td>3.0</td>
<td>4.4</td>
</tr>
<tr>
<td></td>
<td>252</td>
<td>167</td>
<td>2.8</td>
<td>4.2</td>
</tr>
<tr>
<td>White DS</td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td>Owendoher US</td>
<td>97</td>
<td>108</td>
<td>2.6</td>
<td>2.6</td>
</tr>
<tr>
<td></td>
<td>89</td>
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<tr>
<td>Owendoher DS</td>
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<td></td>
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<td>Painstown US</td>
<td>133</td>
<td>108</td>
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<td>4.3</td>
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<td></td>
<td>130</td>
<td>115</td>
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<td></td>
</tr>
<tr>
<td>Painstown DS</td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Morell US</td>
<td>213</td>
<td>108</td>
<td>1.8</td>
<td>1.2</td>
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<tr>
<td></td>
<td>212</td>
<td>115</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Morell DS</td>
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<tr>
<td>Pollaphuca US</td>
<td>12</td>
<td>3.5</td>
<td>0.7</td>
<td>0.5</td>
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<tr>
<td></td>
<td>9</td>
<td>3.6</td>
<td></td>
<td></td>
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<tr>
<td>Pollaphuca DS</td>
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<td></td>
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<td>Glen O US</td>
<td>28</td>
<td>70</td>
<td>1.1</td>
<td>1.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Glen O DS</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Glen V US</td>
<td>26</td>
<td>28</td>
<td>1.4</td>
<td>1.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Glen V DS</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Doonfin US</td>
<td>105*</td>
<td>100*</td>
<td>7.2</td>
<td>7.4</td>
</tr>
<tr>
<td></td>
<td>172*</td>
<td>173*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Doonfin DS</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ardnaglass US</td>
<td>217*</td>
<td>221*</td>
<td>6.6</td>
<td>6.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ardnaglass DS</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spaddagh US</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spaddagh DS</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Total Hardness

Although this does not reflect the whole pollutant-mobilisation potential of the streams, as they were dry-weather samples, they were taken to establish background status.

SEDIMENT QUALITY

Heavy Metals

A standard sediment from the Laboratory of the Government Chemist, Teddington, Middlesex (UK), (product LGC 6139), was employed as a reference. The recovery of heavy metals from the reference sediment was 104% for Cd with a coefficient of variation (CV) of 1%, 96% for Cu with a CV of 2%, 98% for Pb with a CV of 4%, and 96% for Zn with a CV of 1%. Average concentrations of Cd, Cu, Pb and Zn in mg/g of dry weight of stream sediment for the upstream and downstream sites are given in Table 3.

Figure 1 shows the variation of metals upstream and downstream of the sampling sites. Copper concentrations have shown slight increase at downstream of Painstown (20.6 to 30.7 mg/g dry wt) and Rowanstown (38.5 to 53.7 mg/g dry wt). Downstream lead concentrations are higher at Doonfin (15.5 to 46.9 mg/g dry wt). Zinc concentrations are slightly higher at the downstream of Painstown (99.0 to 167.7 mg/g dry wt). The overall comparison of upstream and downstream heavy metal concentrations shows that the downstream concentrations of the heavy metals are not statistically significant (at
p=0.05). All metals show some degree of correlation to each other (multiple or single), the strongest found being a coefficient of determination (R2) of 0.87 for Cu/Zn and a smallest of 0.38 for Cd/Pb. The multiple correlation of Cd against Cu, Pb, and Zn produced R2 of 0.59.

**Polycyclic aromatic hydrocarbons (PAHs)**

Two sites (Glen O’Downs and the Owendoher) have shown significant increases in the downstream concentration of the PAHs detected, the most abundant ones being the medium weight PAHs (see Figure 3). The Glen O’Downs stream was sampled at two downstream stations and

**Table 3. Average concentrations of metals upstream and downstream of sites.**

<table>
<thead>
<tr>
<th>Site</th>
<th>Cadmium mg/g</th>
<th>Copper mg/g</th>
<th>Lead mg/g</th>
<th>Zinc mg/g</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1st Test</td>
<td>2nd Test</td>
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</tbody>
</table>

US = upstream of discharge; DS = downstream of discharge
one upstream station, since the road crosses the stream twice – hence DS(1) and DS(2) in Figure 3(b).

**DISCUSSION**

Pollution from road drainage can arise from accidental spills, wear and tear of the road and vehicle parts, droppings of oil, grease and fuel, and incomplete fuel combustion. Contaminants deposited on the road surface (or the atmosphere) are washed off the road surface and can reach receiving streams during rainfall. Sediment and some pollutants are removed by the drainage systems, although this may not ensure adequate protection of the biota living in the streams. The major pollutants detected in road runoff include the heavy metals Cd, Cu, Pb and Zn and polycyclic aromatic hydrocarbons that are produced during normal operation of a highway.

The mean heavy metal concentration ranges observed in this study are 0.5-4.8mg/g for Cd, 11.2-53.7 mg/g for Cu, 10.6-46.9 mg/g for Pb, and 23.9-216.9 mg/g for Zn. These values are well within the range reported in Maltby *et al.* (1995) and Perdikaki & Mason (1999) for three UK roads (M1, A12 and A14) except for Cd. The values for Cd are relatively high (4-5 mg/g), particularly in the Lyreen and Rowanstown streams. However, this may not reflect the actual pollution levels in these streams because some Irish soils are known to have naturally high Cd levels arising generally from parent material. A report from the Irish Department of Agriculture, Food and Rural Development (2000) stated that the natural “background” Cd concentration in Irish soils (southeastern half of the country) could be as high as 3-4mg/g.

PAHs concentrations in the Owendoher and Glenview stream sediments were higher at the downstream sites, the most abundant ones being Fluoranthene, Pyrene, Benzo(b)+Benzo(k) fluoranthene, which is consistent to that reported in Maltby *et al.* (1995), although the levels detected in this study are very low.

There are no Irish or EU sediment quality guidelines as yet (Crane, 2003). Some EU countries (Germany, Holland, Norway, Sweden and the UK) have developed their own standards and targets independently (Ahlf *et al.*, 2002). The first explicit standards were developed in Canada and the US for monitoring and regulating sediment contamination (Crane *et al.*, 1996). The Canadian Sediment Quality Guidelines for the Protection of Aquatic Life (CCME, 2003) derives Threshold Effect Levels (TELs), also called Interim Freshwater Sediment Quality Guideline (ISQG), and Probable Effect Levels (PELs) from an extensive database containing direct measurements of toxicity of contaminated sediments to a range of aquatic organisms exposed in laboratory tests and under field conditions. Accordingly, effects may be observed in some sensitive species exposed to the TEL, whereas the PEL is likely to cause adverse effects in a wider range of organisms. Table 4 provides summarised values for Cd, Cu, Pb, Zn and PAHs.

According to the above guideline, the contamination levels for most of the sites investigated here were found to be below the ISQG for the heavy metals and between ISQG and PEL for the PAHs detected in the Glenview stream. The toxicity of heavy metals to benthic organisms is dependent on the alkalinity (hardness) of the overlying water. It is
reported that heavy metals are more toxic in soft water than in hard water (Wang, 1987). Aquatic organisms in the Glenview stream are therefore more susceptible to heavy metal toxicity than those in the Rowanstown stream. Microorganisms degrade PAHs, although very slowly. However, heavy metals present in the sediment, which are toxic to these organisms, can further slow the degradation process.

CONCLUSION

Heavy metal concentrations in the stream sediment did not show any statistically significant increase of heavy metals at the downstream sites except for slight increases observed at Doonfin, Slane and Rowanstown. PAHs have, however, showed significant increases in two of the monitored streams (Owendoher and Glenview). The observed concentrations of heavy metals are below the environmental quality standards and chances for adverse effects are low.

ACKNOWLEDGMENTS

The Irish EPA, as part of Environmental RTDI Programme 2000-2006, and NRA funded this research. The authors would like to thank both. Other research partners in the project have collected other data, which will be repeated in later papers.

REFERENCES


INTRODUCTION

The Irish construction industry has experienced unprecedented economic growth over the past decade. In 2004 the construction output represented 22.2% of Gross National Product (GNP) with a value of €27.6 billion (DoEHLG, 2005). Along with the positive economic effect this has had, there also have been some negative impacts. Construction and demolition waste (C&DW) production has increased from an estimated 1.52 million tonnes in 1995 (EPA, 1996) to 11.20 million tonnes in 2004 (EPA, 2005). The government has recognised this dramatic increase by setting out recycling and recovery targets for the construction industry (DoELG, 1998) of 85% by 2013. One of the main difficulties in achieving these targets is the lack of reliable statistics for C&DW production in Ireland.

This paper will outline research carried out by the Centre for Natural Resources and the Built Environment at the Galway Mayo Institute of Technology over a two-year period into the generation of reliable data on C&DW production by:

- producing unit waste generation factors (kg/m²) for the new construction sector;
- identifying the main components of the C&DW stream;
- Developing and testing an audit methodology on 54 construction projects throughout the country.

MATERIALS AND METHODS

The main resource in this study was the third-year students of the BSc (Honours) in Construction Management in the Department of Building and Civil Engineering at the Galway Mayo Institute of Technology. Each year, the students must undertake a six-month work placement on a construction/civil engineering project in Ireland or the UK. Each student acted as a point source assessor on his or her respective work placements measuring the waste production on site. This provided a waste production 'snapshot' of 54 projects over a two-year period (2004 and 2005).

A detailed examination was carried out of three audit methodologies used in the UK construction industry – Skoyles (1978), Coventry et al. (2001) and the Building Research Establishment (BRE). Each method was analysed to identify their suitability within the scope of the study. The main limitation was that these methodologies were based on the assumption that the auditor had only one duty on site, i.e. waste measurement, and therefore was not applicable.

It was decided to develop a practical audit methodology suitable for the conditions of the work placement. Some key steps were identified in the development (Patterson, 1999):

1. Identify all the waste management practices on site, e.g. skip management, on-site burning, and reuse of materials on site.
2. Choose a method for measuring the waste from the following: sort and weigh the entire contents of the skip; sort and weigh a sample from the skip; or conduct a visual assessment of the composition of the skip waste.
3. Select the waste categories. This involves balancing between the accuracy required and the number of different materials occurring on site.
4. Provide on-site arrangements for the audit. This is dependent on the project types and site constraints, as well as the selected method for measuring the waste.
5. Analysis of data to provide the required results, e.g. composition, quantity and cause.

A waste audit book consisting of waste audit sheets (Fig 1) and a supplementary monthly report format (Fig 2) was developed and distributed to the students. To ensure reliable data collection, a C&DW management module was developed as part of their third-year curriculum, consisting of lectures discussing the different aspects of C&DW management and site visits to carry out trial audits.

The methodology was essentially a basic waste skip...
analysis using visual assessment to identify and quantify all the materials being taken off site in skips/containers (Fig 3). Each audit sheet recorded the following information:

- Site location including exact postal address;
- Job description including project category and method of construction;
- Skip size reference including the size of the skip and name of supplier;
- Area code. The site layout could be divided into area codes, e.g. A1, A2, B3, etc, to determine the exact location of the skips;
- Compacted/non compacted;
- Auditor name;

Figure 1. Point source assessment waste audit sheet.

![MONTHLY REPORT](image)

Figure 2. Monthly report format.

Figure 3. Point source assessors skip analysis on-site procedures.
CONSTRUCTION WASTE PRODUCTION INDICATORS

RESULTS

PROJECT CATEGORIES

Each project audited in 2004 and 2005 was divided into project categories as used by the EPA in the National Waste Database Report 2001 (EPA, 2003):

- Residential (new private and public housing);
- Private non-residential (private and semi-state industry, commercial, agricultural, tourism and worship);
- Productive infrastructure (water and sanitary services, airports, harbours, energy and telecommunications);
- Social infrastructure (education, health, public buildings, local authority services and the Gaeltacht).

A number of the developments audited consisted of residential units and commercial units, e.g. retail units, supermarkets, etc. They were categorised as residential construction as in each case the primary construction was residential development with facilities being provided. The number of projects per category is outlined in Table 1.

GENERATION OF WASTE PRODUCTION INDICATORS

Each project ‘snapshot’ audited is termed a point source assessment (PSA). The waste factors are derived from the following data:

- Project reference
- Total waste (m$^3$)
- Total waste (tonnes)
- Completed floor areas (m$^2$)
- Waste factor (m$^3$/m$^2$)
- Waste factor (kg/m$^2$)

For each audited project, the total waste (m$^3$) is divided by the completed floor area (m$^2$) to give the volumetric waste factor (m$^3$/m$^2$). Similarly, the total waste (kg) is divided by the completed floor area (m$^2$) to give the weight waste factor (kg/m$^2$). A mean is then calculated for each category, producing the following results:

- The new residential construction category had an average unit waste factor of 70.27 kg/m$^2$ based on 19 audited projects (Table 2);

Table 1. Number of projects audited per category.

<table>
<thead>
<tr>
<th>Project Category</th>
<th>2004</th>
<th>2005</th>
<th>Total</th>
</tr>
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<tbody>
<tr>
<td>Residential construction</td>
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<td>19</td>
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<tr>
<td>Productive infrastructure</td>
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<td>3</td>
<td>3</td>
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<tr>
<td>Social infrastructure</td>
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<td>4</td>
<td>9</td>
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<td>22</td>
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<tr>
<td>Residential demolition</td>
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<td>0</td>
<td>1</td>
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<tr>
<td>Total</td>
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Table 2. Average waste production factors for new residential construction.

<table>
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<tr>
<th>Ref</th>
<th>Total Waste (m$^3$)</th>
<th>Total Waste (tonnes)</th>
<th>Completed Floor Areas (m$^2$)</th>
<th>Waste Factor (m$^3$/m$^2$)</th>
<th>Waste Factor (kg/m$^2$)</th>
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Table 3. Average waste production factors for new private non-residential construction.

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<th>Total Waste (tonnes)</th>
<th>Completed Floor Areas (m²)</th>
<th>Waste Factor (m³/m²)</th>
<th>Waste Factor (kg/m²)</th>
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<td>233.749</td>
<td>5090</td>
<td>0.082</td>
<td>45.92</td>
</tr>
<tr>
<td>PSA 17</td>
<td>139.560</td>
<td>132.490</td>
<td>5456</td>
<td>0.026</td>
<td>24.28</td>
</tr>
<tr>
<td>PSA 18</td>
<td>20.873</td>
<td>11.237</td>
<td>900</td>
<td>0.023</td>
<td>12.49</td>
</tr>
<tr>
<td>PSA 19</td>
<td>34.563</td>
<td>18.959</td>
<td>867</td>
<td>0.040</td>
<td>21.87</td>
</tr>
<tr>
<td>PSA 20</td>
<td>344.258</td>
<td>239.842</td>
<td>2256</td>
<td>0.153</td>
<td>106.31</td>
</tr>
<tr>
<td>PSA 21</td>
<td>26.618</td>
<td>9.270</td>
<td>285</td>
<td>0.093</td>
<td>32.53</td>
</tr>
<tr>
<td>PSA 22</td>
<td>300.856</td>
<td>182.430</td>
<td>3425</td>
<td>0.088</td>
<td>53.26</td>
</tr>
<tr>
<td><strong>Totals</strong></td>
<td>7240.138</td>
<td>4900.629</td>
<td>83802</td>
<td>2.883</td>
<td>1909.98</td>
</tr>
<tr>
<td><strong>Mean</strong></td>
<td></td>
<td></td>
<td></td>
<td>0.131</td>
<td>86.82</td>
</tr>
<tr>
<td><strong>Range</strong></td>
<td></td>
<td></td>
<td></td>
<td>0.023</td>
<td>-0.506</td>
</tr>
</tbody>
</table>

Table 4. Average waste production factors for new social infrastructure construction.

<table>
<thead>
<tr>
<th>Ref</th>
<th>Total Waste (m³)</th>
<th>Total Waste (tonnes)</th>
<th>Completed Floor Areas (m²)</th>
<th>Waste Factor (m³/m²)</th>
<th>Waste Factor (kg/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PSA 1</td>
<td>53.500</td>
<td>34.650</td>
<td>2080</td>
<td>0.026</td>
<td>16.66</td>
</tr>
<tr>
<td>PSA 2</td>
<td>120.169</td>
<td>97.965</td>
<td>5780</td>
<td>0.021</td>
<td>16.95</td>
</tr>
<tr>
<td>PSA 3</td>
<td>356.750</td>
<td>271.415</td>
<td>6853</td>
<td>0.052</td>
<td>39.61</td>
</tr>
<tr>
<td>PSA 4</td>
<td>289.620</td>
<td>119.538</td>
<td>1817</td>
<td>0.159</td>
<td>65.79</td>
</tr>
<tr>
<td>PSA 5</td>
<td>164.000</td>
<td>144.640</td>
<td>404</td>
<td>0.406</td>
<td>358.02</td>
</tr>
<tr>
<td>PSA 6</td>
<td>124.413</td>
<td>86.947</td>
<td>328</td>
<td>0.379</td>
<td>265.08</td>
</tr>
<tr>
<td>PSA 7</td>
<td>150.531</td>
<td>88.543</td>
<td>2584</td>
<td>0.058</td>
<td>34.27</td>
</tr>
<tr>
<td>PSA 8</td>
<td>468.500</td>
<td>351.216</td>
<td>1344</td>
<td>0.349</td>
<td>261.32</td>
</tr>
<tr>
<td>PSA 9</td>
<td>613.080</td>
<td>399.288</td>
<td>2071</td>
<td>0.296</td>
<td>192.80</td>
</tr>
<tr>
<td><strong>Totals</strong></td>
<td>2340.563</td>
<td>1594.202</td>
<td>23261</td>
<td>1.746</td>
<td>1250.50</td>
</tr>
<tr>
<td><strong>Mean</strong></td>
<td></td>
<td></td>
<td></td>
<td>0.194</td>
<td>138.94</td>
</tr>
<tr>
<td><strong>Range</strong></td>
<td></td>
<td></td>
<td></td>
<td>0.021</td>
<td>-0.406</td>
</tr>
</tbody>
</table>

- The private non-residential construction category had an average unit waste factor of 86.82 kg/m² based on 22 audited projects (Table 3);
- The new social infrastructure construction category had an average unit waste factor of 138.94 kg/m² based on nine audited projects (Table 4);

Table 5. Average waste production factors for new productive infrastructure construction.

<table>
<thead>
<tr>
<th>Ref</th>
<th>Total Waste (m³)</th>
<th>Total Waste (tonnes)</th>
<th>Completed Floor Areas (m²)</th>
<th>Waste Factor (m³/m²)</th>
<th>Waste Factor (kg/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PSA 1</td>
<td>54.133</td>
<td>23.222</td>
<td>295</td>
<td>0.183</td>
<td>78.72</td>
</tr>
<tr>
<td>PSA 2</td>
<td>84.413</td>
<td>54.387</td>
<td>975</td>
<td>0.087</td>
<td>55.78</td>
</tr>
<tr>
<td>PSA 3</td>
<td>51.768</td>
<td>25.673</td>
<td>2349</td>
<td>0.022</td>
<td>10.93</td>
</tr>
<tr>
<td><strong>Totals</strong></td>
<td>190.314</td>
<td>103.282</td>
<td>3619</td>
<td>0.292</td>
<td>145.43</td>
</tr>
<tr>
<td><strong>Mean</strong></td>
<td></td>
<td></td>
<td></td>
<td>0.097</td>
<td>48.48</td>
</tr>
<tr>
<td><strong>Range</strong></td>
<td></td>
<td></td>
<td></td>
<td>0.022</td>
<td>10.93</td>
</tr>
</tbody>
</table>


<table>
<thead>
<tr>
<th>Category</th>
<th>Construction Output in Floor area (m²)</th>
<th>Unit Waste Arisings (kg/m²)</th>
<th>Waste Arisings (tonnes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residential construction</td>
<td>13,958,000</td>
<td>70.27</td>
<td>980,829</td>
</tr>
<tr>
<td>New private non-residential construction</td>
<td>5,153,000</td>
<td>86.82</td>
<td>447,383</td>
</tr>
<tr>
<td>New social infrastructure</td>
<td>88,500</td>
<td>138.94</td>
<td>122,962</td>
</tr>
<tr>
<td>New productive infrastructure*</td>
<td>3,762,314</td>
<td>48.48</td>
<td>182,397</td>
</tr>
<tr>
<td><strong>Total new construction</strong></td>
<td>23,758,314</td>
<td>1,733,571</td>
<td>1,733,571</td>
</tr>
</tbody>
</table>

* The construction output for new productive infrastructure was based on estimates provided by the Department of Environment, Heritage and Local Government (2004).

- The new productive infrastructure construction category had an average unit waste factor of 48.48 kg/m² based on three audited projects (Table 5);
- A waste factor of 813.79 kg/m² was generated for new residential demolition based on one audited project.

APPLICATION OF GENERATED WASTE PRODUCTION INDICATORS

These unit waste production factors can be applied to construction output in 2005 producing a national C&DW production estimate of 1,733,571 tonnes for new construction (Table 6). This estimate excludes any demolition, repair and maintenance categories. To provide a total estimate for all construction activity, the new construction category must be expressed as a percentage of the overall total output.

According to the National Waste Database Report 2001 (EPA, 2003), the new construction categories accounted for 74% of output (m² of floor area) but only 14% of total waste production. The repair and maintenance categories (demolition) accounted for 26% of output (m² of floor area) and 86% of total waste production (excluding soils/stones). If we assume that the estimated figure of 1,733,571 tonnes represents 14% of total waste production in 2005, then the total figure including repair and maintenance is 12,382,650 tonnes (excluding soils/stones).
The National Waste Report 2004 provides an estimate of 8,491,994 tonnes for collection and management of soil and stones. If this is added to the 2005 estimate of 12,382,650 tonnes, then this produces an overall C&DW figure of 20,874,644 tonnes.

The extrapolation to national estimates is reliant on a number of assumptions:

- The CSO data on total planning applications approved in 2005 is a reliable estimate of the total construction output;

**COMPOSITION OF ‘SNAPSHOT’ POINT SOURCE ASSESSMENTS**

**Classification**

The composition of the C&DW stream can vary according to project type/activity. The identification of the individual components is essential in establishing waste prevention and minimisation targets. The methodology used aimed to identify the composition by utilising the appropriate EWC code and a general material description. This produced nine main categories of waste as follows:

- Inert waste;
- Paper, plastics and packaging;
- Timber/wood;
- Plasterboard;
- Canteen waste;
- Building and construction waste;
- Metals (including their alloys);
- Insulation materials;
- Miscellaneous waste.

It must be noted that no excavated material, i.e. soil and stones, was included in the results as none were placed in the skips. The inert waste category recorded consists of materials such as concrete, blocks, brick, tiles and ceramics.

**Composition results**

The composition is expressed in volumes as this identifies the waste fractions that occupied the most space in the skip. The biggest contributors in the overall composition of all the audited projects (Fig 4) were: wood (28%); paper, plastics and packaging (17%); inert waste (16%); metals (13%) and mixed C&DW (11%).

Each category follows a similar trend with:

- Wood, inert waste and paper, plastics and packaging accounting for 66% of total waste produced in the new residential construction category (Fig 5);
- Wood, metals and paper, plastics and packaging accounting for 65% of total waste produced in the new private, non-residential construction category (Fig 6);
- Wood, mixed C&DW and paper, plastics and packaging accounting for 68% of the total waste produced in the new social infrastructure construction category (Fig 7);
- Wood, paper, plastics and packaging and miscellaneous waste accounting for 73% of the total waste produced in the new productive infrastructure construction category (Fig 8).
The main aim of the study was to produce unit waste production factors for new construction in Ireland. Snapshot audits were carried out on 54 projects during 2004 and 2005, generating average waste production indicators for new construction (Fig 9).

There are a number of factors that need to be taken into account when analysing the results of the point source assessments. Each audit was a snapshot measurement of a project over six months, with the majority of the projects at different phases in the construction process. This affected the results where a project in the initial construction phase had negligible amounts of C&DW (excluding excavated materials) as opposed to a project 50% completed. Each auditor was responsible for attaining their own placement, which meant that the results reflected both good and bad waste management practices on site. The number of sites audited (particularly in the new productive infrastructure category) was insufficient to provide a high degree of statistical confidence, especially with the presence of some extreme observations in each category. The audits should continue to generate larger sampling sizes for each category, thereby increasing the statistical confidence in the results.

The compositional breakdown of each category identified the major components of the C&DW stream with wood (including timber pallets); paper, plastics and packaging; inert waste (blocks, bricks, ceramics and tiles) and metals (including alloys) accounting for 74% of the total project composition by volume and 81% by weight. These four categories are potentially recoverable and/or recyclable.

Interestingly, the category paper, plastics and packaging accounted for 15% of the total composition by volume and only 3% by weight. This can be attributed to the use of the conversion factors (Table 7) as outlined in the Waste Management (Landfill Levy) Regulations 2002, which were used in the study. The original function of these conversion factors was to enable landfill operators to calculate the amount of landfill levy payable on certain materials and so are not specific to C&DW stream. The lack of specific conversion factors for the C&DW influences the accuracy in the generation of waste production factors.

This was examined on a new social infrastructure construction project in the Galway region where a comparison was made between the application of the Landfill Levy conversion factors to a visual assessment of skips taken off site and the actual total weight of the same skips weighed at a waste transfer facility (Grimes, 2005). The total weight of the skips weighed was 71.4 tonnes and the total weight using the conversion factors applied to the visual assessment was 230.35 tonnes, which is over three times the recorded weight. This highlights the potential inaccuracy of the conversion factors being used at present.

The other major limitation in generating reliable waste factors is the use of visual assessment and the estimation of waste bulking or air voids. The auditors had to estimate the variation in the consistency of the skip’s total contents by considering:

- The degree of compaction the waste has undergone (if any);

<table>
<thead>
<tr>
<th>Waste Category</th>
<th>m³ to tonnes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inactive or inert waste</td>
<td>x 1.50</td>
</tr>
<tr>
<td>Paper and plastics</td>
<td>x 0.15</td>
</tr>
<tr>
<td>Cardboard, pallets, plasterboard, canteen waste</td>
<td>x 0.40</td>
</tr>
<tr>
<td>Timber and building construction waste</td>
<td>x 0.60</td>
</tr>
</tbody>
</table>
CONSTRUCTION WASTE PRODUCTION INDICATORS

• The poor placement of waste materials creating air voids;
• The irregular consistency of some waste types;
• The irregular shape of some waste containers.

The accuracy of the visual assessment is totally reliant on the expertise and diligence of the auditor. This was demonstrated on a case study in the UK (Coventry et al., 2001) where the visual skip audits were compared with the actual skip contents. A close correlation was found, demonstrating that an experienced auditor can make accurate measurements of the contents.

CONCLUSION

The generation of unit waste factors based on Irish construction projects will enable the industry to benchmark their current waste management performance and provide indicators for future improvements. Construction and demolition waste production has until recently been underestimated in Ireland. The improvement in the reporting procedures has provided a more accurate representation of waste production in the construction industry, as illustrated in the National Waste Report 2004 (EPA, 2005). It is recommended that the methodology discussed in this paper be developed so that the construction industry can voluntarily audit their own activities, thereby producing accurate and reliable statistics.

ACKNOWLEDGMENTS

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The assistance of Dr Shane Colgan of the Environmental Protection Agency, the students on Year 3 of the BSc in Construction Management in the Department of Building and Civil Engineering at the Galway Mayo Institute of Technology, and all the participating companies, is also acknowledged.

REFERENCES


Grimes, D. 2005. The Assessment of Construction and Demolition Wastes arising on Selected Case Study Construction Projects in the Galway Region. MSc Thesis in Construction Management, Department of Building and Civil Engineering, Galway Mayo Institute of Technology, Dublin Road, Galway.
INTRODUCTION

In most European cities, traffic is the most important source of air pollution, and pollution from major roads is also important in suburban and rural areas. They are responsible for emitting a variety of pollutants including NOx, CO and VOC, which consist primarily of hydrocarbons, and particulate matter (PM). Traffic-generated air pollutants are of health concern and hence monitoring of these pollutants is essential. Vehicular dispersion models are essential computational tools for predicting the air quality impacts of emissions from road traffic and are widely used in urban and municipal planning. The Gaussian distribution profile for the dispersion of atmospheric pollutants is widely used as the basis for atmospheric dispersion models.

Over a period of time, due to their simplicity and direct applicability for estimates on a local scale, various versions of the Gaussian line source models have been used for dispersion evaluation from the road. Two such models are the General Finite Line Source Model (Luhar & Patil, 1989)
and CALINE4 (Benson, 1992). This paper evaluates both of these models against a specific experimental dataset of hydrocarbon concentration obtained from the M50 motorway in Dublin, Ireland. The results for acetylene are discussed here. The GFLSM model was applied at a site in Monasterevin, Co Kildare, Ireland, which is primarily a residential centre, to predict the change in air quality due to the opening of its bypass. Monitoring was done both before and after the opening of the bypass to observe the change in air quality and compare it with the GFLSM model results.

### MEASUREMENT SITE

#### AND EXPERIMENTAL SET-UP

**MONITORING SITE AT THE M50**

The M50 motorway is an orbital route for the city of Dublin. At the monitoring site the motorway has a straight alignment with carriageway bearings of 330° and 150°. Six receptors were located on a line perpendicular to the motorway alignment, at distances of 25m, 120m and 240m from either roadside, as shown in Figure 1. The area surrounding the receptors is mostly open parkland with some trees and playing fields. Measurements of traffic flow on the motorway were obtained through induction loops embedded under both carriageways, and hourly traffic flows in either direction were summed to obtain the total vehicle flows. Twenty-one days of traffic data were obtained during the monitoring period. The average hourly traffic flow was 3,936 vehicles per hour, with a relative standard deviation of 23%.

Traffic on this part of the motorway is invariably free-flowing, with an average vehicle speed of 100 km/hr and a 12% HDV content.

The monitoring site is located 6km south-west of the centre of Tallaght, which contains a large number of commercial and light industrial premises. A minor road serving a local residential area lies approximately 350m east of the motorway.

**MONITORING SITE AT MONASTEREVIN**

The sampling site was located on the Dublin side of the town, at the Garda station. The unit was housed at the front of the station in a car park behind a wall of some 3ft in height. Beyond this wall was a footpath. Distance of receptor point from road was about 10 metres. Monasterevin is mainly a residential town with no heavy industry, so the main source of pollutants is the road.

### DISPERSION MODELLING

#### GFLSM DISPERSION MODEL

The General Finite Length Source Model (GFLSM) is based on the Gaussian diffusion equation and is formulated so that it can be applied for any wind direction and any length of the line source. Its solution is based on a modification of an equation derived by Csanady (1972) that allowed receptor concentrations due to emissions from a finite length line source to be calculated for perpendicular winds. The modification by Luhar & Patil (1989) extended this solution to include all possible wind-road angles. The main advantage of this model lies in the simplicity of its application. The main disadvantage of the model is the limited receptor co-ordinates for which concentrations can be calculated. The GFLSM requires the receptor to be located at 90 degrees to the segment of road considered, and the length of the line source should be three times the distance between the receptor location and road (Khare & Gokhale, 2004). The GFLSM uses the following equation to calculate the contribution of a line source to ambient concentrations (Luhar & Patil, 1989):

\[
C = \frac{Q_l}{2\pi \sigma_z (\sin \theta + u_0)} \left[ \exp \left(-\frac{(z-H)^2}{2\sigma_z^2}\right) + \exp \left(-\frac{(z+H)^2}{2\sigma_z^2}\right) \right]
\]

where \(C\) is the concentration, \(Q_l\) is the source strength per unit length, \(u\) is the average wind speed, \(\theta\) is the angle between the wind direction and the road (varying between 0-180 degrees), \(x, y\) and \(z\) are the receptor co-ordinates, \(H\) is the effective source height, \(p\) is the half length of the line source, \(erf\) is the error function and \(\sigma_x\) and \(\sigma_z\) are the vertical and horizontal dispersion coefficients. The term \(u_0\) is the wind speed correction due to traffic wake and has different values for different stability classes as suggested in the GM model (Chock, 1978).

The vertical and horizontal dispersion coefficients are dependent on the downwind distance ‘\(x\)’ and the stability class. The Briggs’ urban dispersion coefficients are employed for \(\sigma_x\) and \(\sigma_z\) (Zannetti, 1990).

Measured traffic, meteorological data and roadway geometry were used as the input parameters to the model. The emission rate, Q and emission factor are determined as a composite using COPERT methodology (Kouridis et al., 2000).

**CALINE4 DISPERSION MODEL**

CALINE4 is a computer-based line source Gaussian dispersion model that uses semi-empirical solutions to the Gaussian dispersion equation (Sharma & Khare, 2001). It was originally developed to calculate CO concentrations but it can be used to predict the concentrations of various other pollutants (NO\textsubscript{x}, inert gases and particulates) in a variety of road networks (Marmur & Mamane, 2003). In the present study this is achieved by using a scaling factor, which is defined as the ratio of the molecular weight of CO to the molecular weight of the hydrocarbon compound of interest (O’Donoghue, 2004). The input parameters required for the model involves roadway geometry, meteorological parameters and measured traffic flow. The emission factors used for computation are considered in grams per mile for each vehicle (Gramotnev et al., 2003).

The basic principle involving CALINE4 is that it individually divides highway links into a series of elements from which incremental concentrations are computed and then summed up to obtain total concentration estimate at a particular receptor location. Each element is further subdivided into three sub-elements and each sub-element is orientated at right angles to the wind direction.

Central to the CALINE4 model is the concept of a ‘mixing zone’ that exists above the roadway where the intense mechanical turbulence, augmented by buoyancy, results in enhanced mixing of pollutants (Held et al., 2003). The primary use of the mixing zone is to establish initial Gaussian dispersion parameters at a reference distance near the edge of the roadway.

The initial vertical dispersion parameter \(\sigma_z\), within the mixing zone is evaluated using an empirical equation (Cadle et al., 1977):

\[
\sigma_z = 1.5 + \frac{t_r}{10}
\]

where \(t_r\) is the pollutant residence time in the mixing zone.
At downwind receptors the horizontal dispersion parameter is computed directly from the standard deviation of the wind direction, as proposed by Draxler (1976):

$$\sigma_f = \sigma_{\theta} f(T/t_i)$$  

(3)

where \(x\) is the downwind distance and \(f_i\) is a universal function of the diffusion time \(T\), and the Lagrangian time scale, \(t_i\). Relationships derived by Hanna (1983) are used to relate Pasquill stability classes and values of \(\sigma_{\theta}\). The equation for \(f_i\) is given as:

$$f_i = \left[1 + 0.9(T/T_i)^{0.5}\right]^{-1}$$  

(4)

where \(T = x/u\) and \(T_i\) is the diffusion time required for \(f_i\) to equal 0.5.

**STATISTICAL PARAMETERS**

For the purpose of comparing monitored and predicted data at both sites, the statistical parameters used are mean, Index of Agreement (IA) (Wilmott, 1981), Normalized Mean Square Error (NMSE), Pearson’s correlation coefficient (COR), the Fractional Bias and the Factor-of-Two (F2), which are defined as follows:

$$IA = 1 - \frac{\left(\frac{c_{\text{pred}} - c_{\text{obs}}}{c_{\text{obs}} - c_{\text{pred}}}\right)^2}{\left(\frac{c_{\text{obs}} - \bar{c}}{\sigma_{\text{obs}}}ight)^2 \left(\frac{c_{\text{pred}} - \bar{c}}{\sigma_{\text{pred}}}ight)^2}$$  

(5)

$$NMSE = \frac{(c_{\text{obs}} - c_{\text{pred}})^2}{c_{\text{obs}} c_{\text{pred}}}$$  

(6)

$$R = \frac{c_{\text{obs}} - c_{\text{pred}}}{\sigma_{\text{obs}} \sigma_{\text{pred}}}$$  

(7)

$$FB = \frac{2(c_{\text{pred}} - c_{\text{obs}})}{c_{\text{pred}} + c_{\text{obs}}}$$  

(8)

and

$$F_2 = \text{the fraction of data for which } 0.5 < \frac{c_{\text{pred}}}{c_{\text{obs}}} < 2,$$  

(9)

where \(c_{\text{pred}}\) and \(c_{\text{obs}}\) are the predicted and observed conditions respectively, \(\bar{c}\) is the mean of all hourly concentration values, and \(\sigma_{\text{pred}}\) and \(\sigma_{\text{obs}}\) are the standard deviations of the predicted and measured data respectively. The index of agreement determines the level to which the model predictions agree with the measured concentrations, with an IA value of 1 implying that the monitored and predicted data are in complete agreement. The NMSE is a fundamental statistical performance parameter, as it gives actual information on the error produced by the model. The normalization assures that in most applications the NMSE does not bias towards models that overpredict or underpredict. An NMSE value of 0.5 implies, on average, a factor of two between predicted and monitored values. The Pearson’s correlation coefficient describes the proportional change with respect to the means of two quantities in question, but it cannot distinguish the type or magnitude of possible covariance. All the above three parameters described are measures of the agreement between the predicted and monitored time series of concentration. The fractional bias is a measure of the agreement between the mean concentrations, and its values range between +2 and -2, where a value of +2 indicates an extreme underprediction and a value of -2 is an extreme overprediction. The IA, R and NMSE are measures of correlation of measured and predicted time series concentration. The FB is a measure of agreement of mean concentration. The factor of two statistically is coarse but is an easily understood measure of the likelihood that an individual model result will agree reasonably well with its equivalent measured value.

**RESULTS**

**RESULTS AT THE M50 MOTORWAY**

**Statistical analysis of the M50 motorway data**

Tables 1 and 2 in this paper present the statistical evaluation of the parameters for the performances of both the GFLSM and CALINE4 at receptor distances of 25 and 120 metres respectively.

The Index of Agreement between the modelled and monitored data showed that, with the increase in downwind receptor distances, both the models were more prone to producing erroneous results. It is also to be noted that the IA values obtained using GFLSM and CALINE4 are very similar to each other; however, it is also observed that in nearly all cases the GFLSM displays a higher IA value than CALINE4, which suggests that it is more likely to give error-free predictions. The FB values shown in Tables 1 and 2 are close to zero, which reflects that there is substantial agreement between measured and predicted values as predicted from both of the models. The Pearson’s correlation coefficients obtained with both models are fairly low. It is to be noted that the R values obtained from both models are quite close to each other and that the GFLSM has a higher value of R as compared to CALINE4, which suggests that the prediction values from GFLSM are more in ‘sync’ with the monitored data than CALINE4.

**Table 1. Statistical results for Acetylene at 25 metres (M50 site).**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Monitored data</th>
<th>CALINE 4</th>
<th>GFLSM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>0.45</td>
<td>0.36</td>
<td>0.36</td>
</tr>
<tr>
<td>IA</td>
<td>1.00</td>
<td>0.44</td>
<td>0.55</td>
</tr>
<tr>
<td>FB</td>
<td>0.00</td>
<td>-0.22</td>
<td>-0.23</td>
</tr>
<tr>
<td>Correlation</td>
<td>1.00</td>
<td>0.29</td>
<td>0.45</td>
</tr>
<tr>
<td>NMSE</td>
<td>0.00</td>
<td>0.6</td>
<td>0.6</td>
</tr>
<tr>
<td>F2</td>
<td>100%</td>
<td>55%</td>
<td>65%</td>
</tr>
</tbody>
</table>

**Table 2. Statistical results for Acetylene at 120 metres (M50 site).**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Monitored data</th>
<th>CALINE 4</th>
<th>GFLSM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>0.14</td>
<td>0.11</td>
<td>0.08</td>
</tr>
<tr>
<td>IA</td>
<td>1.00</td>
<td>0.23</td>
<td>0.26</td>
</tr>
<tr>
<td>FB</td>
<td>0.00</td>
<td>-0.25</td>
<td>-0.54</td>
</tr>
<tr>
<td>Correlation</td>
<td>1.00</td>
<td>0.26</td>
<td>0.35</td>
</tr>
<tr>
<td>NMSE</td>
<td>0.00</td>
<td>3.7</td>
<td>5.1</td>
</tr>
<tr>
<td>F2</td>
<td>100%</td>
<td>20%</td>
<td>20%</td>
</tr>
</tbody>
</table>
NMSE values obtained from both the model applications are very close to one another.

The percentage of F2 values decreases with the increase in receptor locations. This can be attributed to the fact that the receptor near the source has a higher concentration whereas for further downwind receptor locations there is an increase in the frequency of background corrected concentrations, which are often zero. This tends to reduce the F2 values further downwind.

Predicted versus measured concentrations
The monitored and modelled variations of acetylene over the sampling period for receptor locations at 25m and 120m are shown in Figures 2 and 3. Spatial plots of predicted versus measured acetylene concentrations are presented in Figure 4. This indicates the agreement between the measured and modelled long-term average concentration of acetylene over the three different receptor distances of 25m, 120m and 240m. The patterns of the spatial plots computed with both models are similar to the monitored data. Scattered plots between monitored data and predicted data, as obtained from GFLSM and CALINE4, were also plotted within a factor of two for the receptor locations at 25m and 120m for the purpose of comparison of monitored and predicted data. These are shown in Figures 5 and 6. It is observed that with the increase in receptor locations the performance of both models decreases.

Inter-comparison of model predictions
Scatter plots of GFLSM versus CALINE4 predictions for acetylene at different downwind distances of 25m and 120m are presented in Figures 7 and 8.

RESULTS AT MONASTEREVIN
At the Monasterevin site, readings were obtained for each individual hour for all of the monitoring days. The average of all the readings for each of the hours of the day for the periods before and after the opening of the bypass was calculated and the change in air quality was determined by subtracting the average values obtained for each individual hour for the before case from the after case. The reduction in the pollutant concentrations so obtained was plotted against the values obtained by averaging the values of each individual hour as predicted by the GFLSM model. The diurnal profiles so obtained are shown in Figures 9 and 10 for CO and NOx respectively. It is observed that the model tends to overpredict the reductions in CO and NOx concentrations due to the opening of the bypass. Statistical analysis of modelled data and the actually observed reductions in CO and NOx concentrations were performed, which also showed that the model tends to overpredict. These results are shown in Tables 3 and 4.

CONCLUSIONS
It is seen from the above results that the predicted values obtained by GFLSM are in close agreement with the predicted values as obtained
by using CALINE4 for the M50 site. The predicted data from GFLSM and CALINE4 when compared with the monitored data are able to predict the variation of concentration to a certain extent for the M50 site. From the statistical parameters it is quite evident that both models are quite successful in predicting the long-term average concentration. It is seen that the GFLSM predicted values have a better correlation and index of agreement with the monitored data than the CALINE4 values for all the downwind distances. It may be concluded that, for a single stretch of motorway road, the GFLSM is able to predict the concentration of pollutants almost as well as, and sometimes better than, those predicted by CALINE4 values. At the Monasterevin site, it was observed that the GFLSM highly overpredicted the reduction in CO and NOx concentrations. One of the reasons for this could be the Composite Emission Factor (CEF) which is used. Further studies are in progress to determine the applicability of the GFLSM model for more complex road networks.

REFERENCES


Table 3. Statistical results for CO (Monasterevin).

<table>
<thead>
<tr>
<th>Parameters</th>
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<th>GFLSM</th>
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<tr>
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<tr>
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</tr>
<tr>
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Table 4. Statistical results for NOx (Monasterevin).

<table>
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</tr>
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</tr>
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