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LCA Study Investigating the Impact of Construction on Sloping Sites

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LCA Study Investigating the Impact of Construction on Sloping Sites

Prepared for

Forest & Wood Products Australia

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1. INTRODUCTION

The building sector is increasingly aware of the importance of buildings to the sustainability agenda. Buildings in Australia are responsible for approximately 23% of Australia's total Green House Gas emissions (GHG) - as resulting from energy demand in the building sector (CIE, 2007). Economic growth and environmental protection must become and continue to be symbiotic - the environment is the primary supplier of raw materials needed for economic growth which, in turn, relies on a steady supply of those raw materials to allow economic growth (World Bank, 1998). Now economic growth, particularly in the construction industry, is under threat from overuse or finite limits of supply (Common, 1995). External effects such as air and water pollution generated from mining, manufacturing and construction processes can also seriously affect the environment's capacity to continue producing raw materials (Rees, 1999).

Economic growth and the natural environment jointly affect mankind's well-being therefore the efficient allocation of scarce resources is an important issue to both present and future generations (Morel et al., 2001; Scheuer et al., 2003). It is clear that actions are needed to make the built environment and construction activities more sustainable. For instance, the objectives of a private building development may be to maximize profit, efficiency, yearly turnover or employment. In society's view, the ultimate goal of such a development may be to improve social welfare or quality of life, or provide enjoyment. From an environmental viewpoint, however, more building development means more damage to the natural world and depletion of scarce renewable and non-renewable resources. In this way, people tend to go to one of two extremes, either focusing on building development without any consideration of the environment, or criticizing almost any kind of new development in society. Nevertheless, going to either extreme is not an ideal circumstance and an effective balance needs to be struck.

There is no doubt that the construction industry is closely related to environmental degradation (Ahn et al., 2010). Building construction contributes significantly to negative impacts on the environment including consumption of 32% of the world's resources, 12% of the world's fresh water, 40% of the world's energy, 40% of the waste going to landfill and 40% of adverse air emissions (DEH. 2006a). Solutions are already being researched with goals such as minimizing the impact of construction on the environment, recycling building materials to reduce natural resource depletion, and reducing construction waste from on-site processes. Research on green building design and construction to minimize environmental impacts is also underway however the social and economic benefits of green building have yet to be fully investigated and identified (Kimmet, 2005; Robinson, 2005; GBCA, 2006).

Research on the environmental assessment of buildings and materials has been undertaken widely such as the recently launched BPIC LCI project [1] and the

[1] BPIC LCI project is available from the BPIC website: http://www.bpic.asn.au/LCI

environmental sustainability study of building materials undertaken by the Department of the Environment and Heritage (DEH, 2006c). The Australian Life Cycle Assessment Society is also developing a national life cycle inventory database (AusLCI)[2].which will be released soon. However not much has been done on construction processes, particularly cut and fill excavation – hence supporting the reason for this study.

2. LIFE CYCLE ASSESSMENT AND THE CONSTRUCTION INDUSTRY

The idea of Life Cycle Assessment (LCA) was conceived in Europe and in the USA in the late 1960s and early 1970s. It was not until the late 1980s and early 1990s that LCA received wider attention in response to increased environmental awareness (Azapagic, 1999) and concern for energy usage. There was a need for a more sophisticated approach to complex environmental issues. LCA originated from net energy analysis studies to predict future supplies of raw materials and energy resources over a life cycle approach (Azapagic, 1999). During the early studies, energy consumption and efficiency were the main focus and energy-related waste emissions were not considered (Azapagic, 1999). Since the early 1970s, wastes and emissions generated by the production processes were taken into account (Fay & Treloar, 1998; Treloar et al., 2001).

In the early 1990s, concerns over inappropriate claims of LCA results by product manufacturers resulted in action taken by the Society of Environmental Toxicology and Chemistry (SETAC) who initiated a definition for LCA and developed a general methodology for conducting LCA studies. In 1997 the International Standards Organization (ISO) published the first ISO 14040 series to standardize the guidelines and principles on the LCA methodology. In 2006 the ISO 14040 series was revised (ISO, 2006) and is used as the framework for conducting this study. The Standard states that the overarching aims of LCA include:

- identifying opportunities to improve the environmental aspects of products at various points in their life cycle;
- decision-making in industry, governmental or non-governmental organizations (e.g. strategic planning, priority setting, product or process design or redesign);
- selection of relevant indicators of environmental performance, including measurement techniques; and
- marketing (e.g. an environmental claim, eco-labelling scheme or environmental product declaration).

The Standard also states that LCA is still at an early stage of development. Some phases of the LCA technique, such as impact assessment, are still in relative infancy. Therefore, it is important that the results of LCA be interpreted and applied appropriately. Drawing from the commentary in Standard, LCA typically does not address the

[2] AusLCI is an initiative by the Australian Life Cycle Assessment Society and information is available from the website: http://www.auslci.com.au/

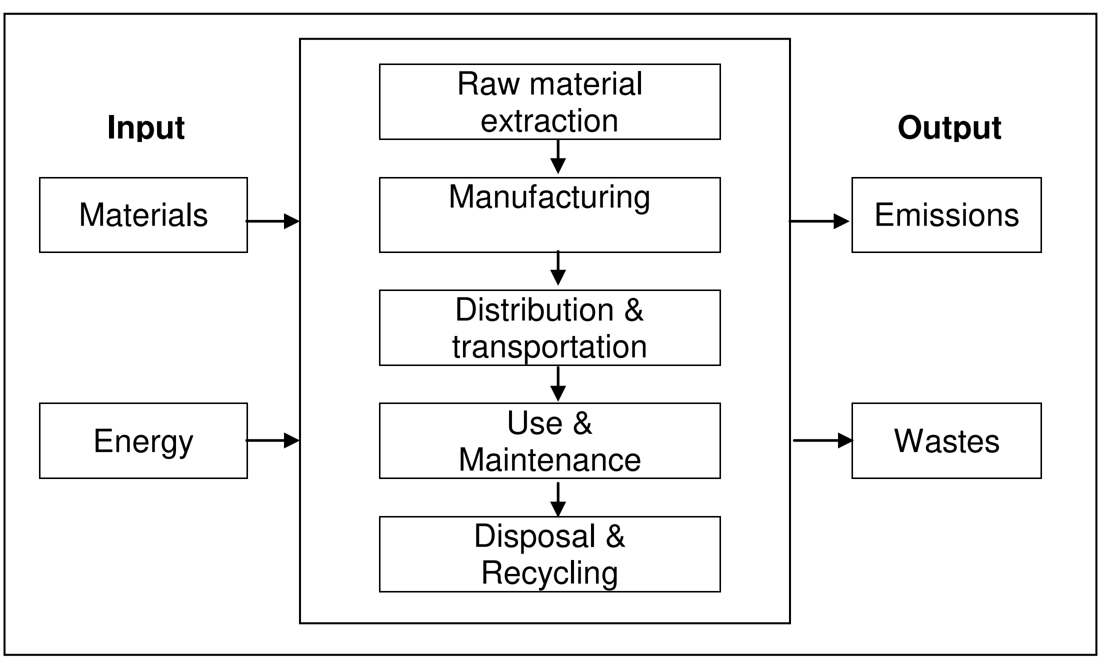
economic or social aspects of a product, the nature of choices and assumptions may be subjective; models used for inventory analysis or to assess environmental impacts are limited by their assumptions; accuracy may be limited by accessibility or availability of relevant data, or by data quality. Generally, the information developed in an LCA study should be used as part of a more comprehensive decision process or used to understand the broad or general trade-offs (ISO 14040, 2006, p iv).

In procedural terms and in accordance with the Standard, LCA starts with a definition of the functional unit and then a quantitative inventory of all inputs and outputs is performed, followed by classification and impact assessment and finally, evaluation of the environmental impact of the system being studied (Bribian et al., 2009). The process of conducting LCA is well documented and received in the industry as a tool to provide a picture of the interaction of an activity with the environment and to facilitate environmental improvements (Azapagic, 1999).

LCA is best defined by SETAC as a process to evaluate the environmental burdens associated with a product, process or activity by identifying and quantifying energy and materials used and wastes released to the environment over the whole life cycle from ‘cradle to grave’, i.e. from extraction of raw materials to ultimate disposal of waste from a product, process or activity (Klopffer, 2006). It has been widely used in Europe and the United States initially for product comparison, but its current application has been extended to include government policy, strategic planning and product design (Bennetts et al., 1995; Kohler & Moffat, 2003; Scheuer et al., 2003).

LCA has been applied to a wide range of assessment which focuses on dealing with the input and output flows of materials, energy and pollutants to and from the environment (Wei et al., 2008). *Figure 1* demonstrates the process of an LCA study.

Figure 1: Input and output flows of materials, energy and pollutants in a project life cycle



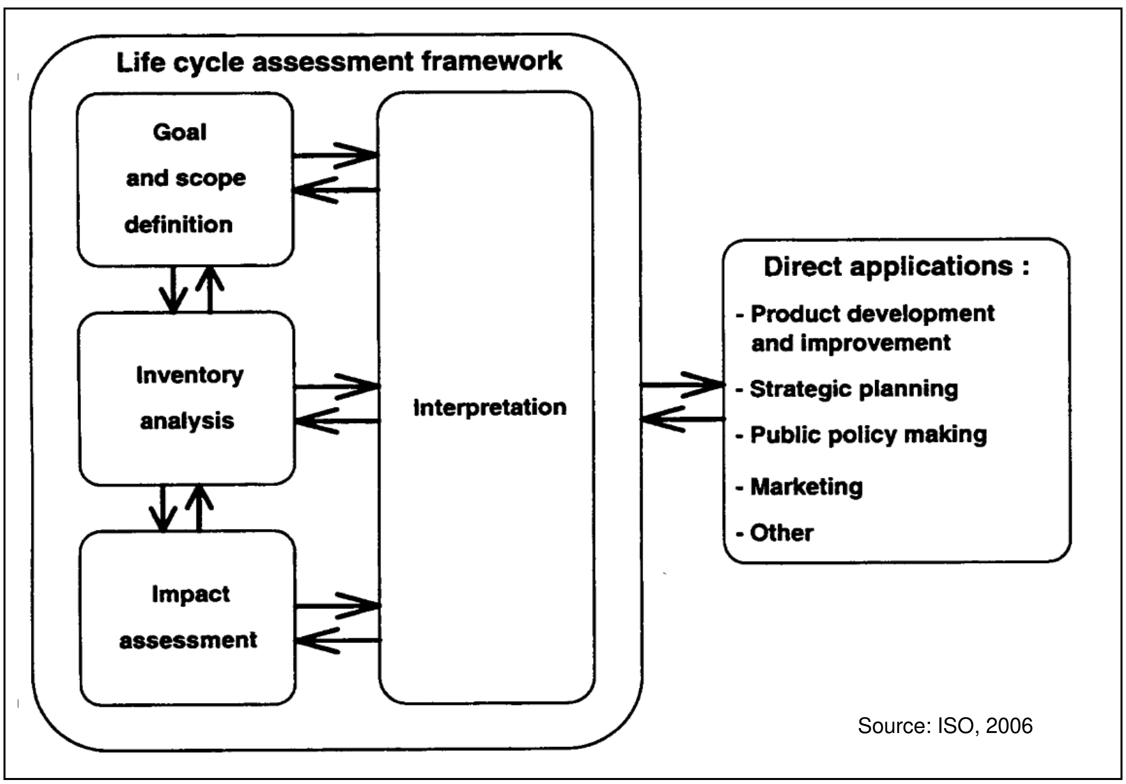
Building on the previously mentioned aims, the principle objectives of LCA are:

- To quantify and evaluate the environmental performance of a product or a process and to help decision makers choose among alternatives; and
- To provide a basis for assessing potential improvements in the environmental performance of the system so as to modify or design a system in order to decrease its overall environmental impacts. This can be done in an overall sense or targeted to improve specific stages during the life cycle.

LCA methodology was governed by ISO 14040 (2006) for principles and framework, and 14044 (2006) for requirements and guidelines. The ISO approach contained in these Standards is fundamental to the standardisation and therefore the generalisabiity of findings pertaining to LCA studies and life cycle inventory (LCI) studies.

An overview showing the intended interaction of these phases is presented in Figure 2.

Figure 2: Overview of the main phases in a LCA study (ISO 14040)



Given the above, LCA can assist construction in addressing problems ranging from excessive consumption of global resources, both in terms of construction and building operation, to the pollution of the surrounding environment (Ahn et al., 2010). Sustainability is an important consideration in construction and the concept of sustainability in construction is about creating and maintaining a healthy built environment and at the same time focusing on minimizing resources and energy consumption, thereby reducing damage to the environment. Construction involves complex processes in transforming lands into habitable environments and a part of this involves excavation. Here, it is notable that some forms of construction “touch the ground” more heavily than others.

LCA has been used in many studies in the building sector as an environmental tool for comparative assessments of materials. Authors such as Cole (1998) have examined LCA on a selection of alternative wood, steel and concrete structural assemblies. Wei et al. (2008) and Kellenberge and Althaus (2009) used LCA to examine flow of material, energy and pollutants for different building components. Verbeeck and Hens (2010) applied an LCA methodology to analyse the whole building while Li et al. (2010) focused on using LCA to study the environmental impact of building processes. LCA study has also been undertaken on site waste management by Cherubini et al. (2009) but an LCA study specifically on excavation and specifically cut and fill construction could not be found in the literature. As such, the current study represents a new dimension to the LCA literature.

3. THE PROJECT

The purpose of cut and fill excavation on sloping land is to create a level building platform on which to build a house – usually in the context of level pad for laying a concrete raft slab floor and footing system. Such excavation changes the pre-existing ground topography to accommodate new building work. In order to create a level building site on steeply sloping land, cutting and filling occurs and the construction of retaining walls is required to stabilize the perimeter of the disturbed area. Drainage is also required for retaining wall construction and may be required to divert surface water such that it does not pond in the levelled area.

Site levelling is likely to be not only the most disruptive activity applied to the area, cutting and filling of housing lots and the construction of large retaining walls has the potential to impact on the amenity of an area as well. It may also detrimentally impact upon the value of adjoining land parcels and more importantly may pose threats to the environment. It disturbs the natural habitat and topsoil of a given site and this poses risks to the integrity of the natural ecosystem. Cut and fill construction alters drainage patterns and soil structure. Like many aspects of construction, the process uses energy and excavated materials may under certain circumstances generate solid waste taken away to landfill. Cut and fill sites may also be subjected to flooding during heavy rain - if sites are inadequately protected with appropriate drainage system, then erosion may occur and sedimentary run-off can leave the site and enter public waterways. Therefore despite the usefulness of levelling land on sloping sites, environmental consequence also need to be considered to minimize impact on the environment.

This study on environmental impact of construction on sloping sites was undertaken to assess and model energy use and greenhouse gas emissions on a range of soil and slopes types in New South Wales (NSW) – primarily drawn from the greater Sydney basin. Design documentation was obtained for 122 projects from various residential home builders in NSW. Since not all projects were suitable for the study, a screening process was employed to examine all the projects in detail to select suitable projects. For instance there was a need to ensure a minimum number of sites in the required slope and soil categories. On this basis the screening process eliminated all but 52 sites. Table 1 summarizes the chosen projects by soil and slope types and additional key data relating to these sites is provided in Appendix A.

Table 1 – Summary of projects by soil and slopes types

Soil type / Slopes type	Sand	Clay	P	Rock
1 in 10	A1 Little Bay A2 Middle Grange A3 Middle Grange A4 Middle Grange A5 Middleton Grange	B1 Burradoo B2 Pendle Hill B3 Helensburgh B4 Gillieston H B5 Moorebank	C1 Castle Hill C2 Auburn C3 Wilton C4 Gymea Bay	D1 Hornsby
1 in 6	A6 Little Bay A7 Bungendore A8 Little Bay	B6 Gillieston H. B7 Casula B8 Woronora B9 Flinders B10 Fletcher B11 Flinders B12 Gillieston H.	C5 Castle Hill C6 Castle Hill C7 Castle Hill C8 Castle Hill C9 Castle Hill	D2 Figtree D3 Wahroonga
1 in 4	A9 Little Bay A10 Little Bay A11 Little Bay A12 Little Bay A13 Little Bay A14 Little Bay	B13 Woronora B14 Flinders B15 Fletcher	C10 Castle Hill C11 Castle Hill	D4 Figtree D5 Newport D6 Newport
1 in 2				D7 Palm Beach D8 Palm Beach D9 Newport D10 Palm Beach D11 Newport D12 Bilgola
Note: Also refers Appendix B for definitions of soil categories.				

With regard to the information in Table 1, it is notable that the original project brief categorised soil types to reflect those stated in AS2870 (Residential Slabs and Footings Code) including the likes of A, S, M, H and E soil categories. In addition, “P” sites (another category in AS2870) were also included in the study as it proved possible to obtain data from such sites during the study. Definitions of these categories are provided in Appendix B.

Of note, the AS2870 soil types essentially categorise soils according to structural foundation performance features. It was realised during the study that this categorisation was not necessarily advantageous for an LCA study because LCA revolves more around energy usage and GHG emissions arising from the excavation process and not around structural performance. For instance, all clays (including M, H and E) require much the same work rate to excavate, whilst sands ("A" classification) are likely to take less work to excavate, and rock (also an "A" classification), more work to excavate. As such, certain soil types from the original brief were either separated or clustered together to reflect this need – as shown in Table 1.

Further to the above, it was found via discussions with local home builders, geo-technical engineering companies and residential land developers that cut and fill construction for mid to steeply sloping sites such as a ratio of 1 in 2 were unlikely to occur except occasionally where rock excavation was involved. As a generalisation, such sites were not common due to the high cost of rock excavation but in the instances where they did occur, it was likely that the majority of the excavation was heavily biased towards cutting rather than equal cutting and filling (Note: solid rock is often self supporting thus allowing a large cut, but excavated rock spoil is typically difficult to re-use as fill). A similar situation occurred for sand sites but mainly for the reason that very steep sand sites were found not to commonly occur in nature.

In executing the project, reliance was placed on utilising the heading structure, layout and methodology provided in ISO 14040. The remaining sections of the report are therefore consistent with the ISO 14040 framework.

4. GOAL AND SCOPE OF THE STUDY

4.1 Goal of the study

The goal and outcome of this LCA study is to provide FWPA, designers and practitioners in the construction industry with an understanding of the environmental impact of construction on sloping sites. An LCA study was undertaken to assess the GHG emissions caused by cut and fill excavation, retaining structure and associated drainage construction for detached residential dwellings in NSW. Where the soil classification and construction details are similar in each State in Australia, the methodology developed in the research and associated insights will be equally applicable to those States. However, where variables such as rock/soil density, truck travel distances, retaining wall details, landfill locations, and fuel sources for the production of electricity differ significantly from the assumptions in this report, then adjustments may be necessary. As required, it is recommended a similar research be conducted in each State so that results can be compared and analysed.

The purpose of the study was undertaken to gain a better understanding of the potential environmental impacts of cut and fill construction on a range of soil and slope types. The specific objectives included:

- To establish a methodology for cut and fill excavation, retaining and drainage construction
- To identify environmental impacts of cut and fill construction for residential projects
- To undertake an LCA study on the activities of cut and fill excavation and associated retaining and drainage construction
- To develop an evaluation matrix that compares environmental impacts and GHG emissions

A further outcome that may arise from the above is an improved ability to find construction solutions that minimize impacts and better attain the ideal of sustainable construction. In addition, this study acts as one of the first of its kind and so it should be viewed as being part of a continuum whereby the generalisability of findings will benefit from ongoing and larger scale sampling and this may also include a wider range of projects.

4.2 Scope of the Study

The purpose of scope definition is to provide a specific boundary of the environmental impact considerations. As mentioned previously the study was intended to provide FWPA, designers and industry practitioners a better understanding on the environmental impact of cut and fill construction. Therefore the LCA methodology stipulated in ISO Standards 14040 and 14044 was applied to quantify environmental impacts of cut and fill construction on a cradle-to-grave perspective. It includes the extraction of the raw materials, manufacturing of the building produces, construction on site, operation and the eventual disposal to landfill at the end of the life cycle. The study includes the plant and equipment that are required in executing cut and fill construction on site, and the initial production and subsequent use of materials that are required for the construction of retaining walls and subsoil drainage.

4.3 Functional unit

The functional unit defines the quantification of cut and fill construction on sloping sites. With regard to the LCA study, it is worth reiterating that the project was undertaken in accordance with the ISO 14040/44 and subsequently includes all upstream and downstream emissions and wastes in the cut and fill activities. In this context, a functional unit acts as a measure of the performance of the functional outputs of the product system. Its primary purpose is to provide a reference to which the inputs and outputs are related. This reference is necessary to ensure comparability of LCA results which is mainly important when comparing different systems.

Following the review of literature, the primary function of cut and fill excavation is to provide a level platform for the construction of a dwelling on a sloping land. The primary function of retaining structure and subsoil drainage are to stabilize the distributed ground around the platform and to provide a water free environment during the phases of construction and operation. Therefore the functional unit in the project has been defined as a detached residential dwelling with a life span of 60 years. The functional unit of cut and fill construction was set to $1m^2$ of the dwelling (building) footprint which typically only deals with the ground floor area of the building. The functional unit of retaining wall and associated subsoil drainage was set to $10m^2$.

4.4 System boundaries

The system investigated was limited to (bulk) cut and fill excavation for detached residential dwellings. Here, the excavation of footings for retaining walls was included in the calculations – as retaining wall construction is a necessary part of the cut and fill system. However, footing construction associated with the house construction has been intentionally excluded because it is considered to be part of a separate building system (i.e. the footing/floor system which changes according to use of concrete, timber and other floor systems). In addition, any further retaining wall and site drainage construction for additional landscaping works was also excluded from the study. Details on the data gathering method and site sampling are provided under Section 5 of this report.

With regard to the above, it is common for the excavation to be designed so that the "cut" and "fill" are roughly equal in volume so that the "cut" soil can be fully utilised as "fill" – thus eliminating any waste soil from the excavation process. On occasion, some sites are more oriented to "cut only" or "fill only" plus various intermediate ratios of the two options. A variety of such scenarios were included in the study.

In the latter of these instances, excess cut materials were assumed to be transported off site and deposited at the nearest publicly available landfill site. With regard to fill, additional materials were assumed to have been purchased from the nearest wholesale supplier of clean fill – in accordance with the fill type specified in the design documents and in accordance with fill requirements in AS2870 (Residential Slab and Footings Code).

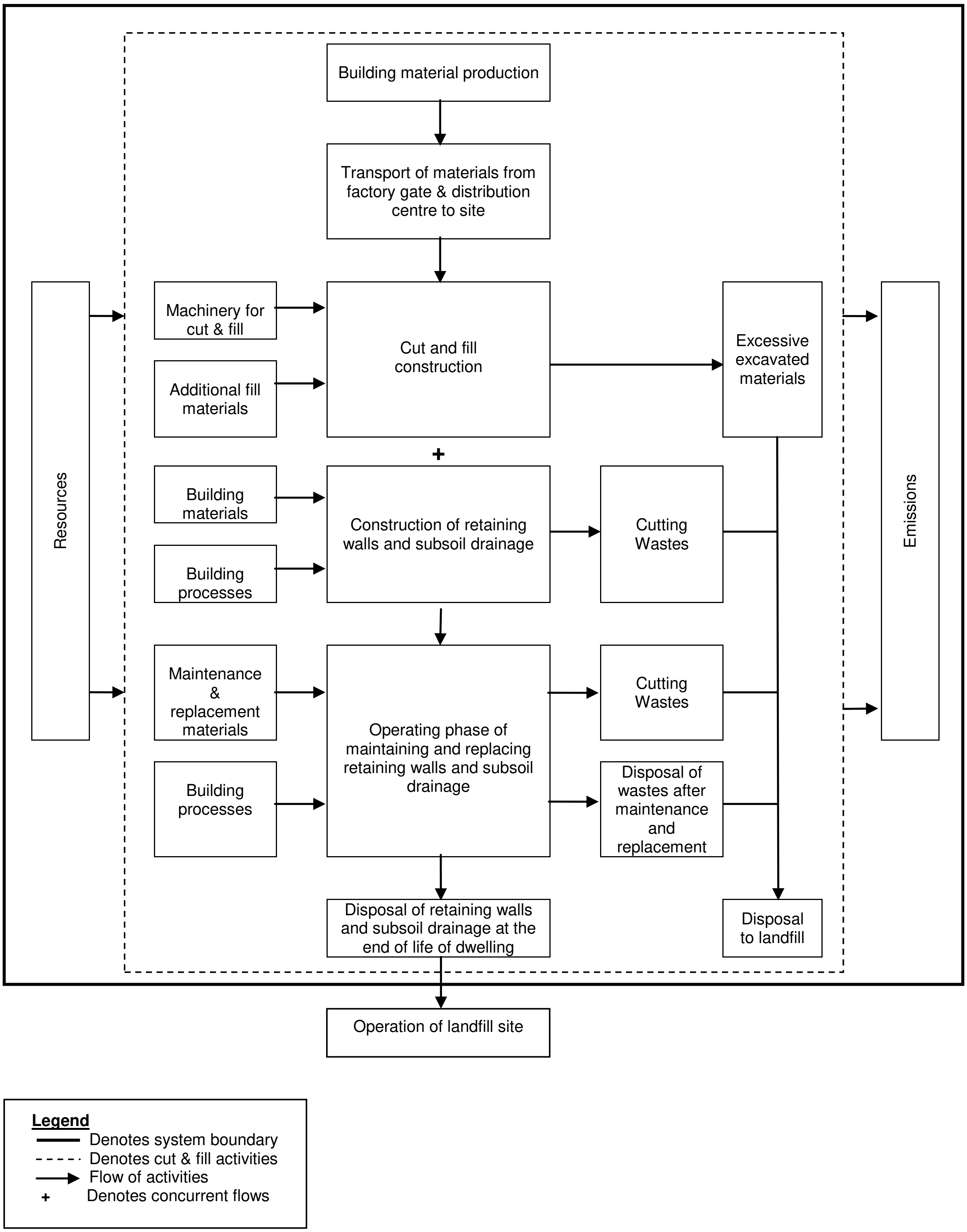
Retaining wall and associated subsoil drainage systems were assessed in accordance with the design documents received at the time of the study from the relevant construction contractor. Any subsequent variations to the design are not part of the scope and have not been considered in the study. Drainage associated with retaining wall construction was included in accordance to the design and standard industry practice.

The system boundaries applied in this study were 'cradle to grave', which means that all impacts of the manufacture of building products, their transport, the construction and operating phases, and the final disposal of the product after its useful life were considered. The project focused specifically on the material and energy flows, and Global Warming Potential (GWP) as the main issues that were measured in the project. Other aspects such as non-methane volatile organic compounds, particulates, human and aquatic toxicity, eutrophication, and acidification, were considered less relevant in impacting on cut and fill construction and were therefore not considered in the study. In support of this, it was apparent that many assumptions would be involved in considering how these issues were impacted by cut and fill construction to the extent that it would be hard to attribute such impacts with any confidence.

The materials and energy consumption, and environmental consequences including emissions to air and water, land uses and solid waste production are the primary concerns and all attempts have been made to identify and quantify major flows to and from the environment. In addition, the relevant processes such as fuel consumption, power production, and transportation are regarded as necessary components of the study. Cut and fill equipment such as excavators and trucks are critical in getting the job done. To a certain extent, environmental impact in relation to construction phases is the result of equipment operations, which usually consume electricity and/or diesel fuel. Consequently, pollutants are generated and natural resources are consumed in the production of electricity and petroleum. Thus, the environmental impact of equipment operation is indirectly determined by energy consumption. *Figure 3* summarises the system boundary for the project.

The project was undertaken in terms of comparative studies on of a range of soil and slopes types in order to identify and quantify the environmental impact and difficulty of excavation to aid decision making. Though it is beyond the scope of this study to suggest improvements that may arise from the project findings, there is potential for others to utilise the findings for this purpose. In addition and of somewhat related relevance to this point, the project does not include comparison with competing methods of construction on sloping land such as suspended concrete or timber floor construction.

Figure 3: The system boundary of the cut and fill project



4.5 Allocation procedures

Allocation procedure is a process of dividing environmental impacts within processes that cross the system boundaries of an LCA. This is more applicable to multi-input and multi-output processes. For processes with multiple inputs and outputs allocation of the environmental burden to each of the co-products is necessary, as prescribed by ISO 14040.

The processes for cut and fill construction will closely relate to the diesel consumption for plant and equipment. The production of diesel fuel is a co-product of different fuels arising from in oil refinery processes. The allocation process used in diesel production is based on energy content and it is assumed that the allocation process has already been dealt with when the data was documented. At the end-of-life stage, it is assumed that all materials go to landfill and no recycling process crossing system boundaries was considered. Landfill is considered as a multi-input process and allocation has been dealt with in the background data based upon physical composition of inputs. However the operation of the landfill has not been included in the study. The multi-output processes in the life cycle of materials used for the construction of retaining wall and subsoil drainage have also been dealt with during the manufacturing process and the main allocation key used for multi-output process is mass.

4.6 Life cycle impact assessment methodology

A main objective of the LCA is to assess the inputs of resources required in a unit process and to determine the outputs to the environment. Output with similar environmental impacts can be grouped and aggregated to a single parameter, known as an impact category. As stated in ISO 14040/44, if comparative assertions from life cycle impact assessment (LCIA) are disclosed to the public they should be internationally accepted impact categories, and be environmentally relevant to the spatial and temporal context.

It was determined during the scope development process that a comprehensive set of environmental impact categories were to be investigated. In order to provide a basis to obtain environmental profiles of cut and fill construction, an investigation was conducted to collect data on energy consumed by plant and equipment for construction activities, materials used for retaining walls and subsoil drainage construction, and waste discharge from each unit process. Material quantities for the retaining wall and subsoil drainage were estimated from the design documentation. The energy input to each unit process included diesel fuel consumption of plant and equipment for excavation, transportation and disposal of waste to landfill. The quantity of energy consumption was estimated to be the predicted running time of the equipment multiplied by the average consumption of electricity and/or fuel per unit of time.

Once materials and energy were determined, a list of environmental profiles associated with each unit process was established using the GaBi LCI database (http://www.gabi-software.com/australia/databases/us-lci-database/). GaBi is an LCA software developed by PE International based in Germany that contains an Australian LCI database. In addition and as appropriate, other Government published literature was also used e.g. IPCC (1995), DCCE (2010) and DEH (2006b & c) publications. For the purpose of undertaking the analysis the impact categories were determined to best represent the issues relating to cut and fill construction. The time period chosen to calculate global warming potential (GWP) was 100 years.

Energy consumption was estimated in terms of primary energy demand i.e. as a methodology to assess a product's, process's or activity's concerning overall environmental impacts throughout its life cycle (Ding, 2005; Huijbergts et al., 2010). Primary energy demand is the total of direct and indirect energy use. It includes the energy consumed during the extraction, production, use and disposal of the raw and auxiliary materials. During the combustion of fossil fuels for energy GHG is generated and the quantity of gas produced depends on the carbon content of the fuel. Primary energy is different from the energy used at the end of the consumption line. An energy efficiency coefficient is used to convert primary energy consumption into end energy.

The increase of global temperature is related to the amount of greenhouse gases in the atmosphere. Climate change is often used as an outcome of global warming. Global warming potential (GWP) is a measure of the emission of greenhouse gases contributing to global warming. GWP is a measure of all gases set in relative terms to carbon dioxide which has a GWP of 1 kg. For instance, other gases are expressed as a multiple of carbon dioxide e.g. methane (CH4) is expressed as 21 kg CO_2-equivalent for a 100 years time range of assessment. The GWP for greenhouse gases is published by the Australian Greenhouse Office in their Factors and Methods Workbook (DEH, 2006b). Relevant values from the Workbook are included in Appendix C.

5. LIFE CYCLE INVENTORY ANALYSIS

Inventory analysis involves data collection and calculation procedures to quantify relevant inputs and outputs of a product system. These inputs and outputs include the likes of resources and releases to air, water and land associated with the system. Interpretations may be drawn from these data and the data also constitutes the input to the life cycle impact assessment (ISO 14040, 2006, p. 7).

The study included data collection in the following categories for the cut and fill construction on sloping sites:

- Fuel consumption for plants and equipment for cut and fill
- Materials for retaining walls
- Materials for subsoil drainage relating to retaining walls
- Emissions to air, water and soil
- Wastes

5.1 Data Quality Requirements

Data quality requirements were driven by the needs of the study. Some specific aspects relating to the study and prompted by ISO 14040 include:

- time-related coverage – projects used in the study were either under construction or had been completed in the last 12 months;
- geographical coverage – projects used in the study were drawn from the greater Sydney basin;
- technology coverage – projects reflect contemporary detached residential construction practice, especially volume housing construction practices;
- consistency and reproducibility of the methods used throughout the LCA – the methods used in the study are realistically consistent and repeatable;
- sources of the data and their representativeness – the data gathered for the study is thought to be representative of a small sample of projects that were available at the time of the study only; and
- precision, completeness and representativeness of the data – the data is only representative of small sampling sets which are limited to the slope, soil types and construction methods used on those sites.

5.2 Data collection and calculation procedure

To estimate the work in respect to resources and energy required for cut and fill construction, a breakdown of cut and fill construction was developed in accordance with the design documentation for project received during the study. A summary of the inputs and outputs for the cut and fill construction is included in Appendix D at the end of the report. The construction process was therefore divided into the following unit processes:

1. Cutting to the upper portion of the site to level the land (Note: Any excavation relating to stripping and storage of topsoil for later use has not been taken into account in the study).
2. Filling to the lower portion of the site to make up the level to the design platform level
3. Construction of retaining walls and subsequent subsoil drainage systems including backfilling of trenches with specified materials
4. Deposit of excess excavated materials off site to the nearest identifiable and publicly available landfill site
5. Purchase of additional materials as specified for filling from the nearest listed wholesale supplier of such materials.

5.2.1. Initial construction

For the selected sites as shown in Table 1, a quantity take off was undertaken for all processes and materials pertaining to cut and fill construction including cut and fill, retaining wall and subsoil drainage. The quantities were derived using Cost X software and all quantities were tabulated in an Excel spreadsheet. Cost X is an on-screen measurement software which can be used to measure from scanned PDF or CAD drawings and this techniques was utilised in the study. The volume of cut and fill was measured based on the differences between site topography and the required platform level. As part of this, allowances were also made for the bulking of cut soil where use for fill and/or where excess spoil was taken away from site to another location. Quantities of retaining wall and subsoil drainage were measured based on the construction details provided. Waste factors for each material were also taken into account as part of this process, with attention to factors defined in Forsythe et al. (2001).

The LCA model for retaining wall and subsoil drainage was created using the GaBi 4.4 software system. The databases contained in the software provide the LCI data of the raw and processed materials used in the background system. Secondary data was also used from literature, previous LCI studies and life cycle databases. Table 2 summarises the average quantities of cut and fill by soil and slopes types and by proportion.

Table 2 – Summary of average cut & fill and retaining wall by soil and slopes types

Item / Soil types	Slopes	Cut	Fill	Cut	Fill
		(m^3)		Proportion (%)	
Sand	1:10	71	46	61	39
	1:6	402	70	85	15
	1:4	424	153	73	27
Clay	1:10	81	77	51	49
	1:6	107	84	56	44
	1:4	126	46	73	27
P	1:10	50	44	53	47
	1:6	136	21	87	13
	1:4	39	-	100	-
Rock	1:10	35	40	47	53
	1:6	44	35	56	44
	1:4	77	124	38	62
	1:2	507	32	94	6

There were three different types of retaining structure used for the projects. They were:

- Treated timber log retaining walls for relatively low slope sites[3]
- Concrete block retaining walls with concrete core fill and reinforced footings for poorer soil types and steeper slopes, and
- Structural steel post retaining walls with treated timber log infill pieces for poorer soil types and steeper slopes.

In conjunction with the measurement activity, the work output rates used in the study were averages from data obtained from various sources for the types of excavation equipment required for different soil and slopes types. In gathering this data, four excavation contractors used by the building companies who supplied the sites for the

[3] Leachate from timber retaining walls has not been taken into account in this study as insufficient quantitative evidence of a leachate problem could be identified

project were contacted and interviewed. They were asked about their preferred excavation equipment for a model housing site and their estimation of associated work output rates if applying different soil types and slope categories to that site.
In addition consultant quantity surveying firms were also contacted to provide information on work output rates for cut and fill construction. They were asked for the work output rates based on the same scenario as used for excavation contractors. In the end, the work output rates for cut and fill excavation were averaged from the information obtained and used for the study.

Cut and fill construction involved the use of plant and equipment such as excavators, rock breakers and trucks. The use of plant and equipment requires the consumption of diesel fuel during the construction process and consequently generates pollutants. Therefore the environmental impact of plant and equipment is indirectly determined by energy consumption. The total energy consumption was obtained by multiplying the average fuel consumption of plant and equipment per unit of time on site. The average fuel consumption for plant and equipment was sourced from civil contractors and equipment manufacturers. As one example of this, fuel consumption for a 15 tonne excavator, cutting and filling onsite, was estimated to be 15 litres/hour and for an $11m^3$ truck carrying fill from site, 40 litres/100kms (Note: differences exist in comparing the two rates whereby the truck will only carry about $6m^3$ of insitu soil due to a bulking rate of approximately 1.5. Plant and equipment associated with the excavation and filling process were quantified and assessed from the point of being floated from the distribution centre to site. However, the process of raw material extraction and manufacturing of the actual plant and equipment have been excluded from the study since this represents an extremely minor contribution in the study.

Excess cut materials were assumed to be transported off site and deposited at the nearest public landfill site. Table 3 summarises the distances of the assumed landfill sites for the various projects used in the study. Additional filling materials (as specified in the design documentation) were assumed to be obtained from the nearest available wholesale outlets. Table 4 summarises the distances of the projects from such material suppliers. According to the geographical location of the sites and the landfill, it is estimated that the transportation distance of excess excavated material averaged in the range of 4 to 29 km, whilst the distance for additional fill materials was about 6 to 36 km.

Table 3 – Distances between projects and landfill sites

Landfill sites	Average distances from projects (km)
Kurnell Landfill Site, Kurnell, 2231	26.0
Horsley Park Landfill, Horsley Park, 2164	14.4
Bungendore Tip, Bungendore, 2621	7.0
Cessnock Waste & Ruse Centre, Cessnock, 2325	28.8
Helensburgh Landfill, Helensburgh, 2508	4.0
Lucas Heights Resource Recovery Park, Lucas Heights, 2234	17.1
Eastern Creek Landfill, Eastern Creek, 2766	26.9
Wollongong Reserve Recovery Park, Kembla Grange, 2526	19.1
Moss Vale Landfill, Moss Vale, 2577	11.5
Kimbriki Resource Recovery Centre, Terrey Hills, 2084	15.6

Table 4 – average distances between projects and fill suppliers

Fill suppliers	Average distances from projects (km)
Middle Grange,	12
Burradoo	8
Flinders	32
Gillieston Height	6
Castle Hill	11
Hornsby	19
Figtree	36
Newport	36

5.2.2 Maintenance and replacement during operation

Excavated land achieved from cut and fill construction is considered for the purposes of the study to require no maintenance, should the retaining wall and subsoil drainage be constructed to the required standard. In deliberating on this, separate landscaping and site improvements – such as paving and associated drainage – may impact in some way on the maintenance of the levelled platform but the ability to accurately quantify and generalise this impact is considered to be unrealistic, hence justifying why such work has been left out of the analysis.

The three types of retaining walls as identified in the study require virtually no regular and scheduled maintenance (if constructed correctly) during the 60 year life of the dwelling. Therefore no maintenance of retaining wall and subsoil drainage was considered in the study. Of note, it was assumed that concrete block walls and structural steel post retaining walls will last the life span of the building. Treated timber log retaining walls were considered to not require replacement based on the use of H5 timber and appropriate section sizes as specified in "Timber Service Life Design"

(FWPA, 2010) - capable of lasting the full service life of the dwelling. Of note, this assumption is based on such walls being installed professionally and with appropriate attention to structural durability and drainage of moisture.

Subsoil drainage was required to all types of retaining walls and was assessed in accordance with the design for the retaining wall. The subsoil drainage included PVC slotted pipe wrapped in geo-fabric sock and backfilled with blue metal or gravel. It was assumed that subsoil drainage was only be replaced if the retaining wall structure was to be demolished and no interim maintenance was allowed as such work is typically concealed behind the retaining wall.

5.2.3. End-of-life

It was assumed that all retaining wall and subsoil drainage would be sent to landfill following deconstruction at the end of the building's life cycle. No recycling was allowed for in the study even though this may occur to an unknown level of predictability. Further, transport to the landfill was included but all emissions relating to the operation of the landfill such as use of bull dozers were excluded. Demolition of the house was excluded from the study i.e. the overall house relates to a larger system that goes beyond the boundaries of cut and fill construction. Further, demolition of timber retaining walls and subsoil drainage was assumed to be undertaken using manual labour under the assumption that the house would still be in place, thus, no plant or equipment such as bull dozers was involved. As a result of these assumptions, demolition was considered as insignificant and therefore disregarded in the study. In addition, the potential of demolished retaining wall timber to rot in the ground, and allow gas emissions, was considered low due to the (assumed) H5 rating of the timber. This coupled with work by Ximenes et al. (2008) concerning rot and timber degradation at landfill, has meant that gas emissions from rotting retaining wall timber is considered unlikely and therefore has also not been taken into account in the study.

6. LIFE CYCLE IMPACT ASSESSMENT

The life cycle impact assessment results have been calculated for total primary energy consumption and GWP for all projects. The results include initial material extraction and production, construction on building sites, transport, operation over a 60 year life span for the building, and eventual disposal to landfill at the end-of-life.

Of note, analysis for slopes with a steepness ratio of 1:2 were only available for rock sites and not for sand, clay and P sites. As discussed earlier in the report, sites of this type could not be found to occur because cut and fill was largely seen as an unrealistic design solution for sites greater than 1:4 in slope. With regard to this, difficulties in obtaining a representative sample for a 1:2 slope have limited the insights possible for this slope category.

The results of the analysis have been presented in two contexts:

1. Cumulative energy demand and GWP per metre square of building footprint (ground floor area)
2. Cumulative energy demand and GWP per metre square of gross floor area.

Given the above, Building Footprint (BF) represents the part of the building that touches the ground (i.e. the ground floor area). Gross Floor Area (GFA) represents the overall floor area of the building. Depiction of the comparative difference between BF and GFA is included in Appendix E. In such instances, cumulative energy demand and GWP for multi-storey dwellings will typically be higher for BF compared to GFA because energy is only divided by the building footprint and not the total building area (as spread over multiple storeys).

6.1 Cumulative energy demand (MJ/m^2)

Cumulative energy demand for cut and fill excavation, retaining walls and subsoil drainage were calculated using GaBi software, the GaBi LCI database, and data from government publications mentioned previously in Section 4. Cumulative energy demand was expressed in terms of square metres for both BF and GFA to facilitate comparison. Table 5, *Figure 4 and 5* summarise the average cumulative energy demand per square metre for BF and GFA by soil and slope types. These figures include cut and fill, retaining wall and associated drainage construction.

Cut and fill activities represent approximately 74% of the cumulative energy demand (see Section 6.3). These calculations include the fuel consumption for excavators on site. In addition, the cumulative energy demand also takes into consideration the fuel consumption of trucks in taking excavated materials away to landfill and the delivery of extra filling materials to site from suppliers (where fill was greater than cut for a given site). Further, retaining wall construction - also incorporating associated drainage works - is included in the cumulative energy demand calculations.

Table 5 – Average cumulative energy demand per m^2 of building footprint and gross floor area by soil and slopes types

Item / Slopes	Sand		Clay		P		Rock	
	BF	GFA	BF	GFA	BF	GFA	BF	GFA
	(MJ/m^2)		(MJ/m^2)		(MJ/m^2)		(MJ/m^2)	
1:10	118.7	85.0	72.4	55.9	36.6	18.8	233.0	138.3
1:6	311.1	141.6	238.1	167.7	146.9	71.2	272.0	241.5
1:4	494.7	193.5	440.4	272.0	142.5	66.1	320.0	177.0
1:2	-	-	-	-	-	-	2469.6	932.6

Figure 4 – Cumulative energy demand (MJ/m^2) per building footprint by soil and slopes types

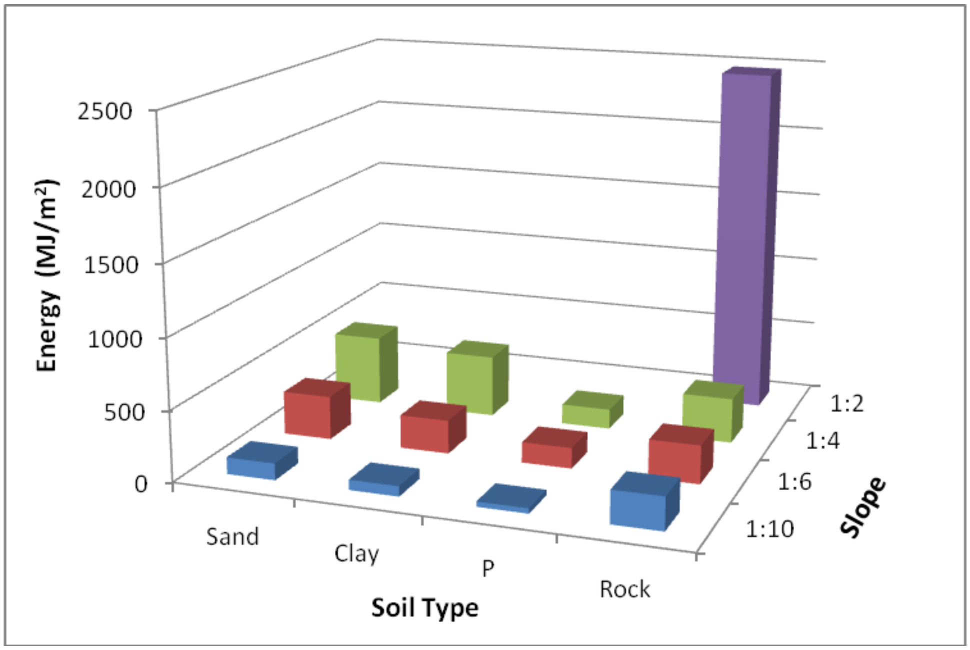
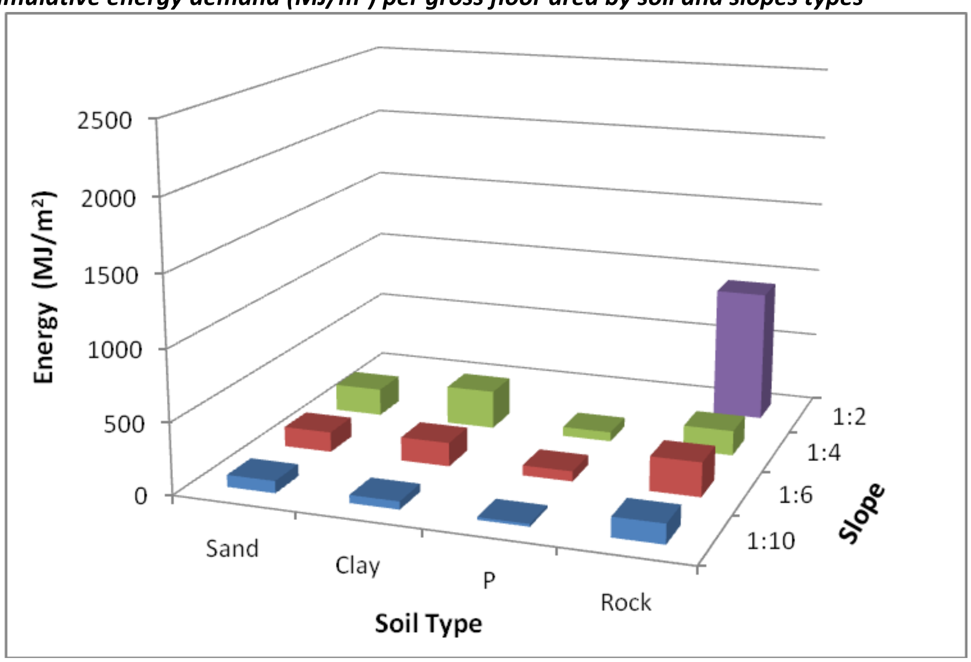


Figure 5 – Cumulative energy demand (MJ/m^2) per gross floor area by soil and slopes types



As indicated in Table 5, *Figure 4 and 5* average cumulative energy demand per square metre of GFA was lower than the BF in most cases i.e. because for BF, total energy is divided by the ground floor area only. Using this unit helps highlight the fact that designing buildings to occupy a smaller footprint will reduce energy used in cut and fill construction (compared to larger footprints).

From Table 5, *Figure 4 and Figure 5*, it can be said that cumulative energy demand increases as slope increases for some soil groups. Even so, it can also be said that there is not necessarily an evenly spaced progression in cumulative energy demand as slope increases. There are also some areas where the data follows less clear trends. Some reasons and insights into this include:

- From the study it was realised that cutting consumes considerably more energy than filling during the cut and fill process. So variances in the proportion of cut and fill for a given site can cause significant differences in cumulative energy demand compared to another site. Of note, there was a need in the study to obtain a sample of sites that covered the different soil and slope categories, but was later realised during quantification of excavation, that steeper soil categories involved a bias towards cut and less towards fill. As a result, approximately 63% of the projects required 65% or more cut, a further 27% fell in a more equal range where cut and/or fill did not exceed a ratio of 65:35. The remaining 10% required 65% fill or more.

- In making calculations relating to cartage of excess cut material, it was assumed that the resulting spoil was taken away to landfill and though this may represent a worst case scenario for cumulative energy demand, alternative strategies such as spreading excess fill onsite will also cause additional energy usage and GWP, and so the difference compared to the chosen assumption may be marginal.

- Retaining wall structures represented approximately 25% of cumulative energy demand (see Section 6.3). Even so, not all the sites studied required retaining walls (25% did not involve retaining) thus creating a different cumulative energy demand profile for these sites. Within this group, 54% of the non-retaining wall sites (7 sites) occurred on shallow sloping 1:10 sites, a further 23% (3 sites) occurred on sites with a slope of 1:6 and the remaining 23% (3 sites) occurred on sites with a slope of 1:2. Such instances appear to occur where able to batter the soil or where self supporting rock is involved. Where retaining was involved, there was also variance in the cumulative energy demand according to the type of wall used. Here, timber retaining walls consumed the least amount of energy, being approximately 756 MJ/m^2; timber walls with steel posts consumed 1028 MJ/m^2; whilst concrete block retaining walls consumed the most amount of energy at approximately 1403 MJ/m^2. The data was checked to see if certain types of retaining walls were used more consistently on certain slope categories. No clear trends emerged other than to say that concrete block walls were the only types used on the small sample of steeply sloping rock sites in the study. For other soil and slope types, multiple types of retaining wall were used.

- Typically on most sites, the levelled excavation area was slightly larger than the BF (but ultimately this larger area was then generalised into BF and GFA energy and GWP calculations). For instance, additional area was made up of the levelled apron around the BF and some sites had a further levelled area where “squaring-up” the excavation for houses where the BF was made up of overlapping rectilinear shapes e.g. the inner corner of an “L” shaped building would typically include a levelled area cutting across the inner corner rather than excavating purely along the building outline. These additional areas impacted more on BF than GFA as a unit of measure and may impact on different sites to different extents.

- Some steeply sloping sites involved cut only and also utilised suspended floor construction to mediate the slope on the site. These sites deserve special mention as they involve most of the P sites used in the study. Such sites typically involved a significant cut to accommodate a garage/storage level. Since this level did not span the full depth of the dwelling, a suspended floor (built on top of the garage walls) was then used to bridge across the remaining width (and slope) of the dwelling. Of note, the small garage area compared to the rest of the dwelling represented created a relatively small BF and it appears that this has had an independent effect on energy calculated for such sites.

- The shape, size and orientation of the dwelling had a changing impact on the amount of excavation work required from one site to the next and this subsequently impacted on and cumulative energy demand calculations.

6.1.1 Observations concerning Rock Sites

In most cases, rock sites used more energy than other sites for comparable slope categories. Reading from Table 5, the extremely high cumulative energy demand for rock sites with a 1:2 slope was primarily due to the massive amount of cut for these sites. Extensive time and energy was required by the excavator during the cutting and associated rock breaking processes. Additional energy was used in taking the excavated rock away to landfill or recycling[4]. As mentioned previously, cutting is more energy intensive than filling but in addition, the high work rates required of rock excavation, made it approximately eight to ten times higher than for other soil types.

On lesser sloping rock sites, it was notable that despite a strong bias to cutting, some minor filling also took place. Here, some fill was retained from the cut where fines could be retrieved and crushed during the excavation process (i.e. by rolling over it with the excavator). This was to some extent achievable with the likes of sandstone (as occurs in the Sydney basin) but difficult to achieve with harder rocks such as Basalt and Granite (i.e. unless using dedicated rock crushing equipment which was not used on the sites studied as such methods were considered uneconomical on detached housing sites).

Of note, it appears that from the large number of sites canvassed for the study (122 in total) cut/fill sites of 1 in 2 slope only tended to occur where rock was involved. The

[4] For the purposes of calculating energy used in carting fill away, the landfill depot and recycling location were assumed to be located in the same place

total lack of other soil types at this slope indicate that it is typically unrealistic and uneconomical to use cut and fill construction in such situations – as confirmed by the contractors, developers and geotechnical engineers contacted during the study.

6.1.2 Observations concerning Clay, Sand and P Sites

Clay, sand and P soils showed more consistent trends in terms of the relationship between energy and slope. For instance, in clay soils only very low energy was required for 1:10 sites and this increased both progressively and significantly for 1:6 and 1:4 sites. The reason for the very low cumulative energy demand relating to 1:10 sites appears to be due to the lesser volume of excavation and retaining wall structure per square metre of floor area than the other two slope types. Of note, sand followed seemingly similar trends.

P sites varied slightly in terms of the relationship between energy and slope. There were less consistent results. For instance, the 1:6 slope required more energy per square metre than the 1:4 slope. It seems this was the result of a higher volume of cut and fill between the two categories – the 1 in 6 category was approximately three to four times greater than 1:4 sites.

6.2 Global warming potential (GWP) (kg CO_2-e/m^2)

Global warming potential (GWP) was calculated for all the projects and results are presented in Table 6, Figures 6 and 7 which summarise average GWP by the BF and GFA for all soil and slopes types. For GWP, similar trends to cumulative energy demand existed in so far as the link between increase in slope and increase in GWP. Even so, parts of the data did not show such clear trends and the same reasons stated for causing a lack of clarity under Section 6.1, also still apply here.

Adding to the above, the GWP results appear to be reasonably closely related to cumulative energy demand. This is likely to be the case since energy production in Australia is predominantly produced via coal-fired power stations which carry high CO_2 content - CO_2 is the major component in the measurement of GWP. Approximately 94.7% of GWP was related to cut and fill activities whilst retaining wall structures only represented 5.2% and the end-of-life stage was less than 1% (see Section 6.3). The 94.7% GWP represents a larger proportion than the same component viewed in the context of cumulative energy demand (refer Section 6.1). The reason for this appears to be that the production of fuel (as used in cut and fill processes) creates higher carbon emission compared to the emissions in the manufacture of retaining wall materials.

Of the projects that included retaining walls (65% of the total sites), approximately 49% used concrete block walls, followed by 38% timber and 13% involving both timber and structural steel posts. Timber retaining walls had the lowest GWP at approximately 65 kg CO_2/m^2, structural steel with timber logs at 111 kg CO_2/m^2, and concrete block retaining walls at 276 kg CO_2/m^2. All these values include a value of 19 kg CO_2/m^2 for subsoil drainage[5].

Of the retaining walls systems studied, treated timber had the lowest negative environmental impact assuming use of appropriately sized H5 treated timber and assuming other aspects of the retaining wall are designed to last the assumed 60 year life span of the building. If this is not achieved and wall replacement is required, a significantly different result would occur.

Table 6, *Figure 6 and 7* demonstrate consistent results in so far as showing GWP increases with increases in slope steepness. The steeper the slope the higher the GWP content per square metre of floor area. As alluded to in previous discussion, GWP per square metre of GFA is lower than GWP per square metre of BF in all cases. Working towards a smaller building footprint will reduce GWP and this is especially the case as site slope increases –particularly steeply sloping rock sites. For instance, the GWP per square metre for rock sites with a slope of 1 in 2 was three times lower for GFA compared to BF. Therefore reducing the building footprint by constructing multi-level dwellings can help to reduce environmental load on cut and fill construction.

As with cumulative energy demand, P sites demonstrated an inconsistent result in comparison to the other soil types. This appears to be a result of more cut and fill activity per square metre of floor area than for other soil types. It may also be a result of the site specific nature of P sites (associated with problematic soil conditions) relative to the consistency of other soil types.

Table 6 – Average GWP per m^2 of building footprint and gross floor area by soil and slopes types

Item / Slope	Sand		Clay		P		Rock	
	BF	GFA	BF	GFA	BF	GFA	BF	GFA
	($kgCO_2$-e/m^2)		($kgCO_2$-e/m^2)		($kgCO_2$-e/m^2)		($kgCO_2$-e/m^2)	
1:10	72.0	44.7	39.1	30.8	19.7	10.4	137.4	81.6
1:6	224.5	98.1	80.9	54.7	100.7	49.2	189.7	164.8
1:4	248.4	99.2	116.3	72.0	43.1	20.8	260.4	145.6
1:2	-	-	-	-	-	-	2394.7	892.5

[5] Note: drainage has been treated as a constant across all three forms of retaining wall construction

Figure 6 - GWP ($kgCO_2$-e/m^2) per building footprint by soil and slopes types

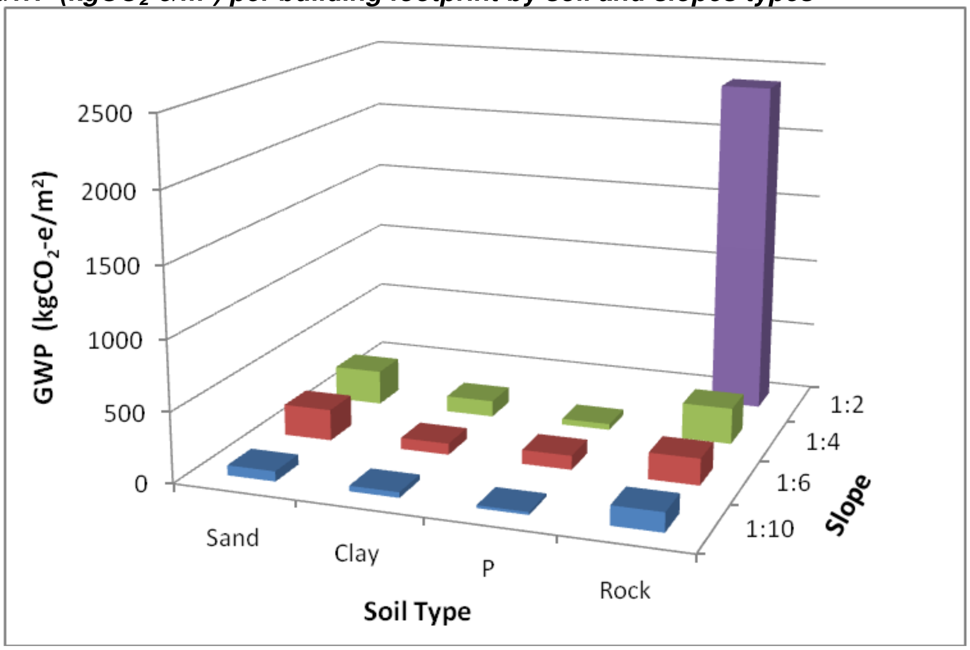
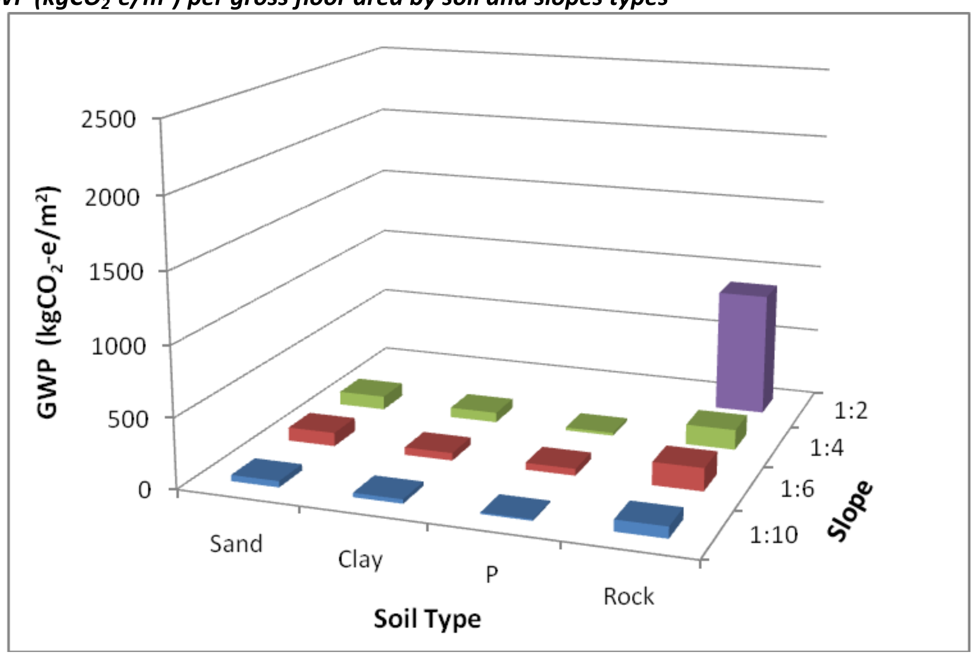


Figure 7 - GWP ($kgCO_2$-e/m^2) per gross floor area by soil and slopes types



6.3 Analysis of cumulative energy demand and GWP by stages

An analysis was also undertaken to investigate the cumulative energy demand and GWP by stages during the life of the dwelling and results are presented in *Figure 8 and*

9. Both figures indicate that cut and fill construction has both the highest cumulative energy demand and GWP, followed by retaining walls. Cut and fill represents 74% and 95% respectively for cumulative energy demand and GWP. The combined total of cut and fill and retaining wall construction totalled 99% and 99.9%. The end-of-life stage represents 1% to less than 1% in both cases. No allowance was appropriate or required for demolition and replacement during the operating stage. Of note, this assumption is conditional for timber retaining wall construction on the assumption that H5 treated timber is used and appropriate detailing is also used, to achieve a service life of 60 years – thus lasting the entire life span of the building.

Figure 8 –Cumulative energy demand by stages

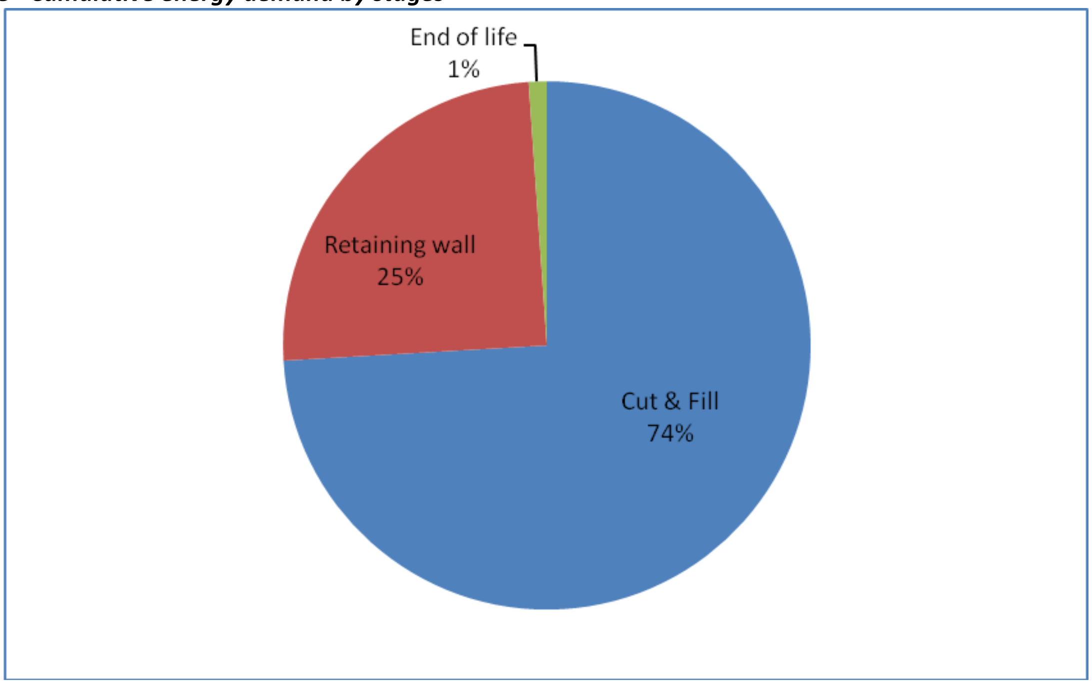
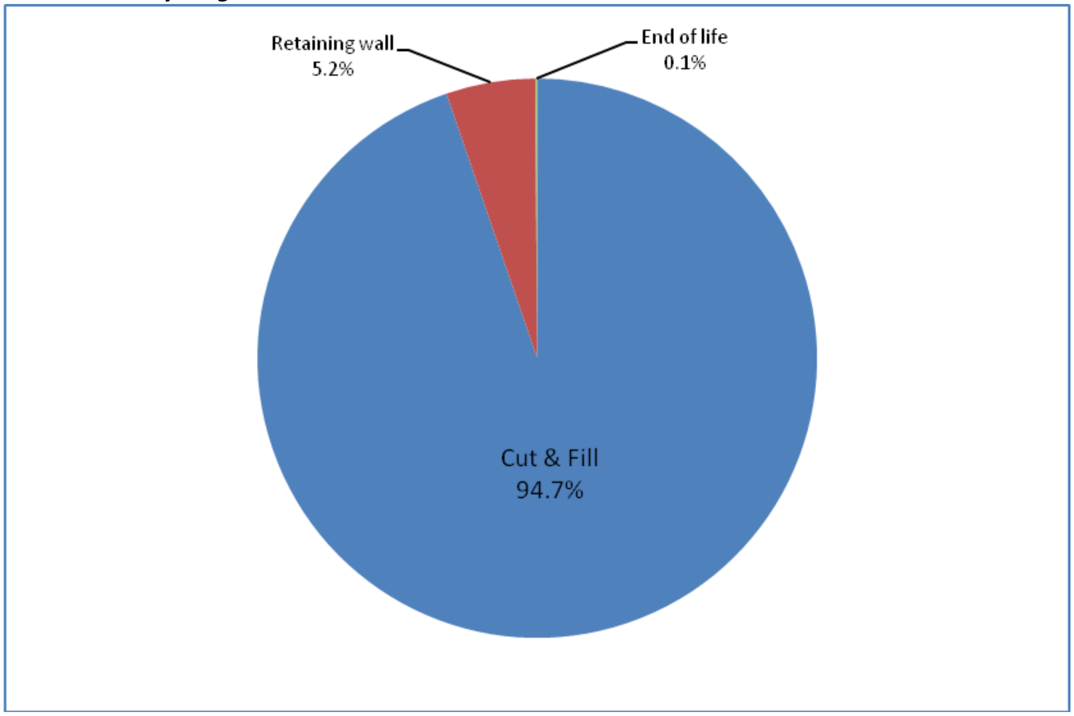


Figure 9 – Total GWP by stages



6.4 Regression Analysis of Cumulative Energy Demand and GWP by Soil Type and Building Footprint

For each soil type, a regression analysis was used to help analyse cumulative energy demand per square metre of BF (MJ/m^2) against site slope, with a view to better explaining the variance in the data. The results are presented in *Figures 10 to 17*. Slope is expressed in degrees in the Figures and so to assist conversion of this with previous discussion of slope expressed as a ratio, Table 7 provides a basis for conversion

Table 7 – Basis for conversion for slope in degrees and as a ratio

Slope Conversion table	
Slope in degrees	**Slope as a ratio**
5.7	1:10
9.5	1:6
14.0	1:4
26.6	1:2

In interpreting the analysis, the main issues of interest reported in each figure concern the "r" value (correlation coefficient) and "R2" value (coefficient of determination). The R2 value is used to statistically model the prediction of future outcomes based on the correlation trends in the data already recorded i.e. as presented in the figures below. It shows the proportion of variability in a data set that is explained by the statistical model. The "r" value is calculated as the square root of R^2 which explains the degree of relationship between two variables.

Leading on from the discussion above, Figure *10 and 11* present the relationship between cumulative energy demand and slope for sand and rock soils. The correlation coefficient of 0.85 and 0.78 respectively for sand and rock soils indicates a strong positive correlation between cumulative energy demand and slope. The R^2 value of 72% and 61% show that the variance in the cumulative energy demand can be explained by the slopes shown in *Figures 10 and 11*. There were three outliers in the rock sites and if removed, the correlation coefficient increases to 91%.

Figure 10 – Cumulative energy demand of sand by slopes

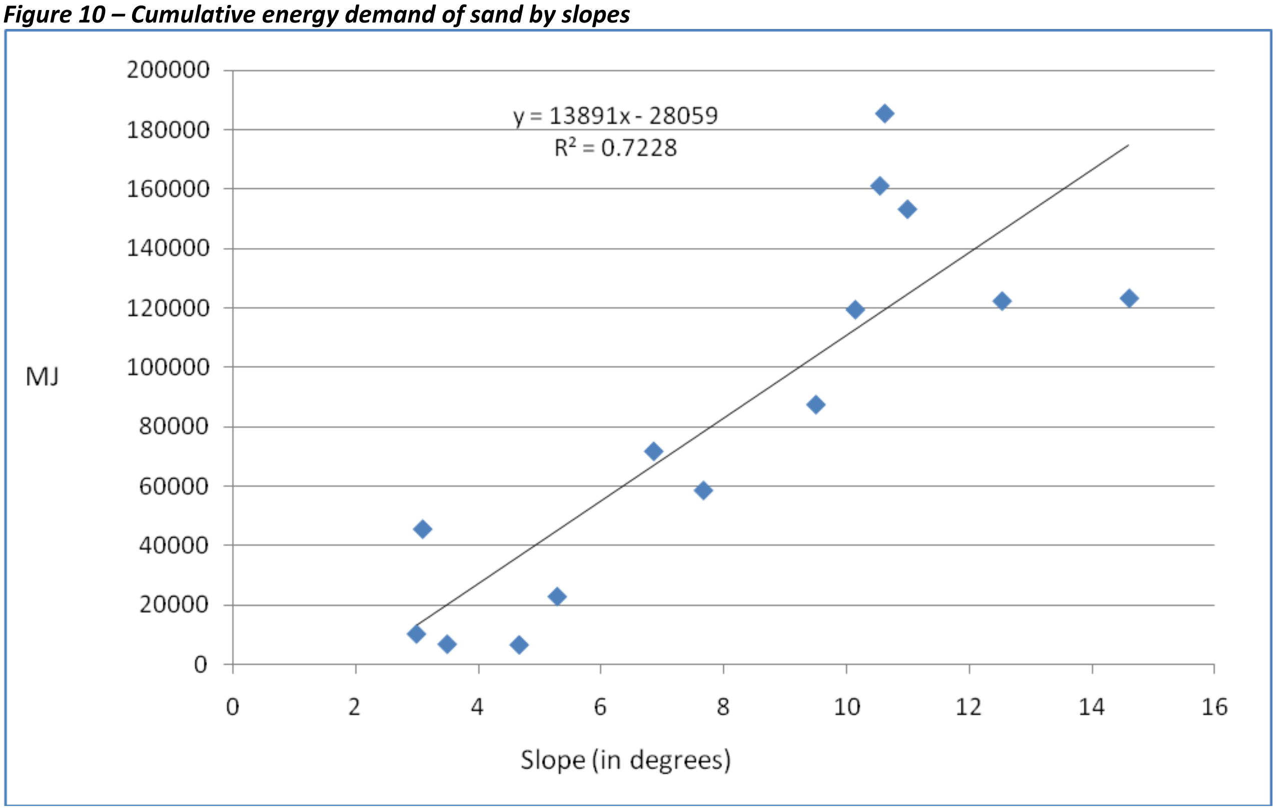


Figure 11 – Cumulative energy demand of rock by slopes

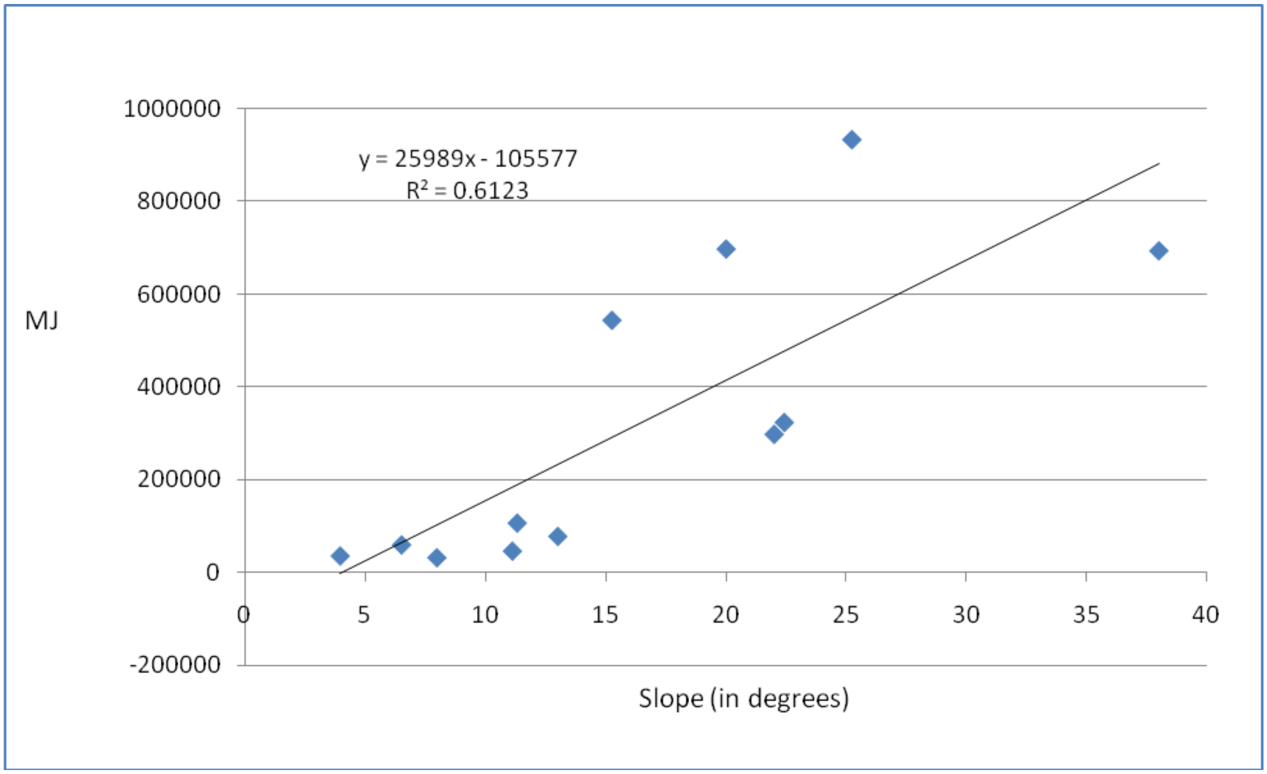


Figure 12 and 13 present the relationship between cumulative energy demand and slope for clay and P sites. In both cases the correlation coefficient of 0.48 and 0.33 indicate positive but not strong correlation between the variables. The R^2 values imply that only 23% and 11% of the variance in the cumulative energy demand can be explained by the slopes shown in *Figures 12 and 13* (respectively). Other variables may have also contributed to the cumulative energy demand such as size of sites. There appear to be outliers in both cases that may have contributed to the results.

Figure 12 – Cumulative energy demand of clay by slopes

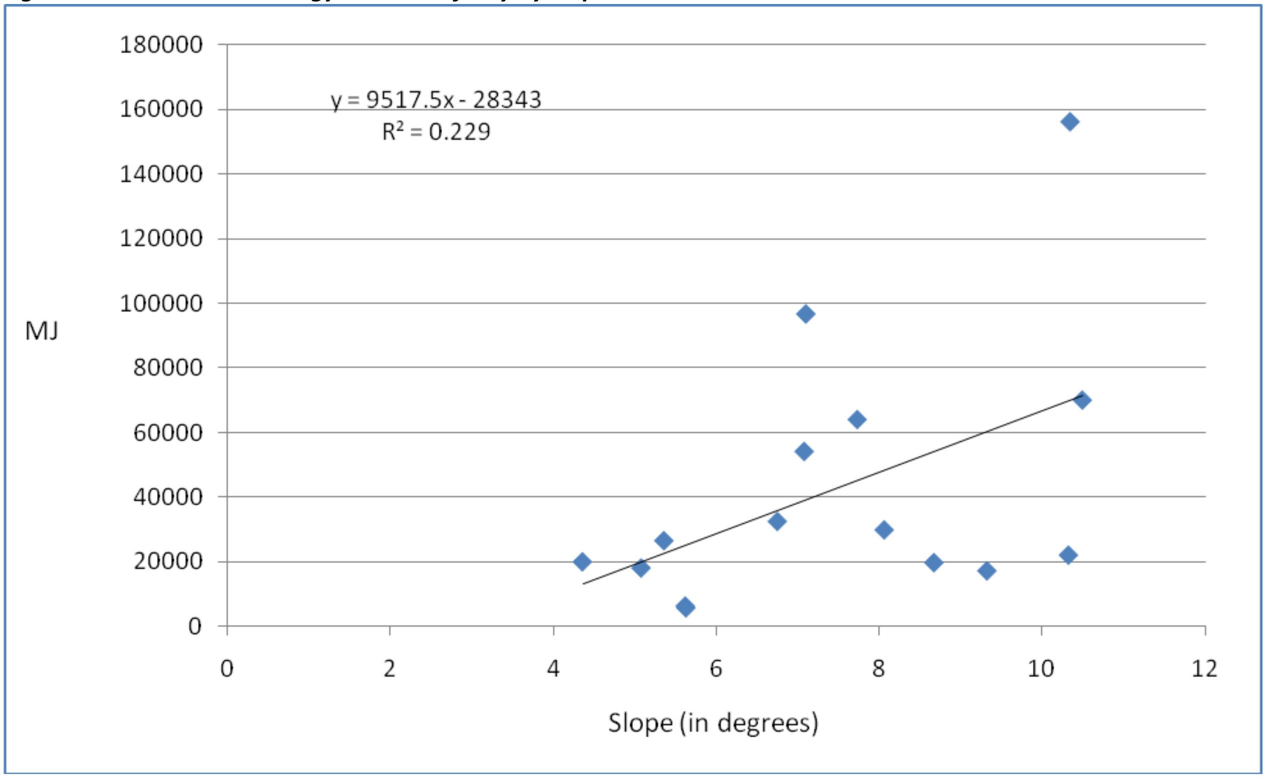
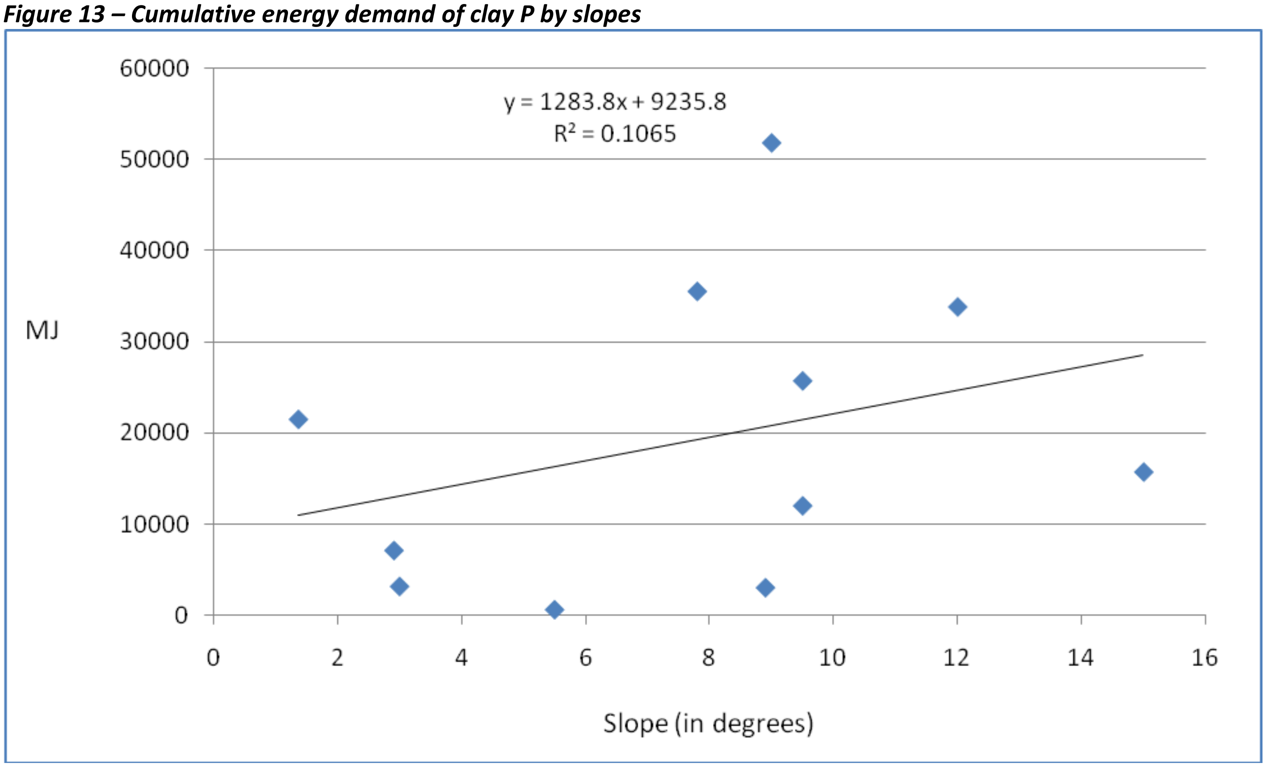


Figure 13 – Cumulative energy demand of clay P by slopes



Similarly GWP (kg CO_2-e/m^2) was analysed by soil and slope type and the results are presented in *Figures 14 to 17*. The results are similar to those for cumulative energy demand. For instance, the figures indicate that slope has a positive correlation with GWP and GWP increases as slope increases. Even so, this correlation is not as strong as exhibited for cumulative energy demand.

Figure 14 and 15 present the relationship between GWP and slope for sand and rock sites. Similarly, the correlation coefficient of 0.85 and 0.75 indicate a positive and strong correlation between the variables. The R^2 value implies that 72% and 56% of the variation in the GWP can be explained by the variation in the slope. Outliers appear for both sand and rock sites in the figures. As demonstrated for cumulative energy demand, removal of these outliers is likely to increase the strength of the correlation.

Figure 14 – GWP of sand by slopes

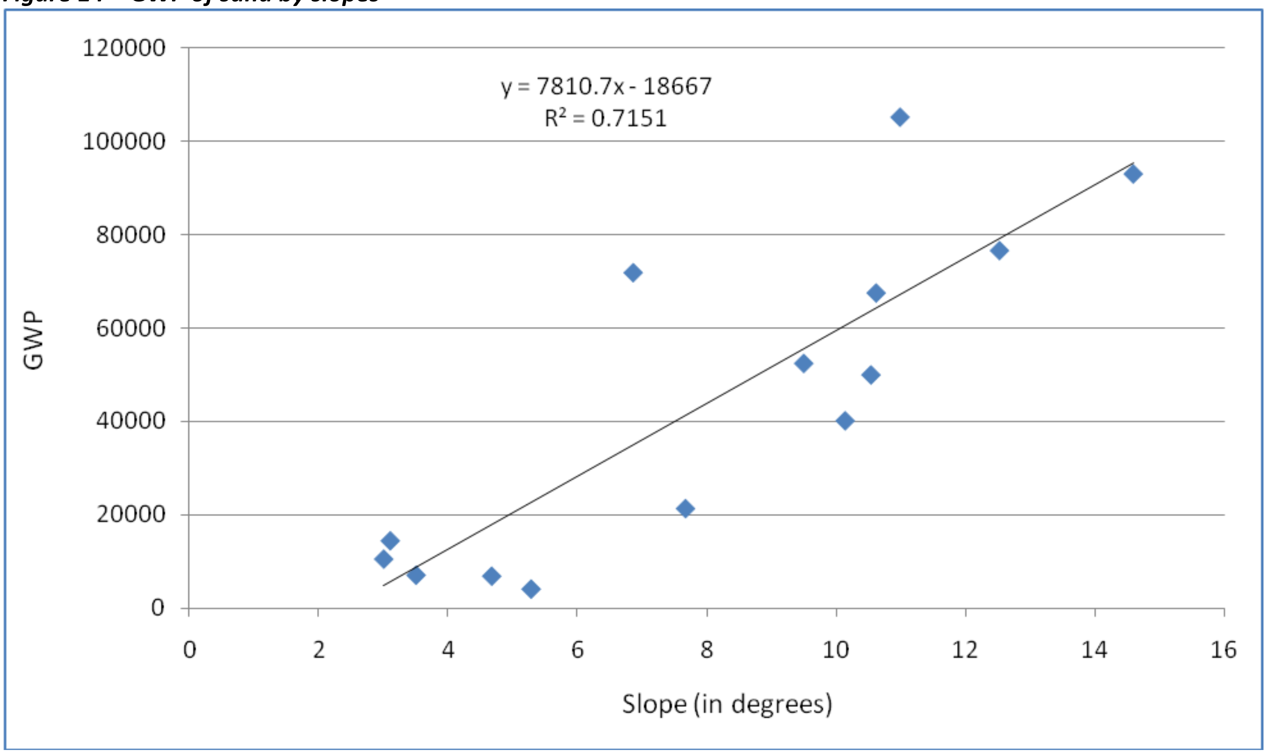


Figure 15 – GWP of rock by slopes

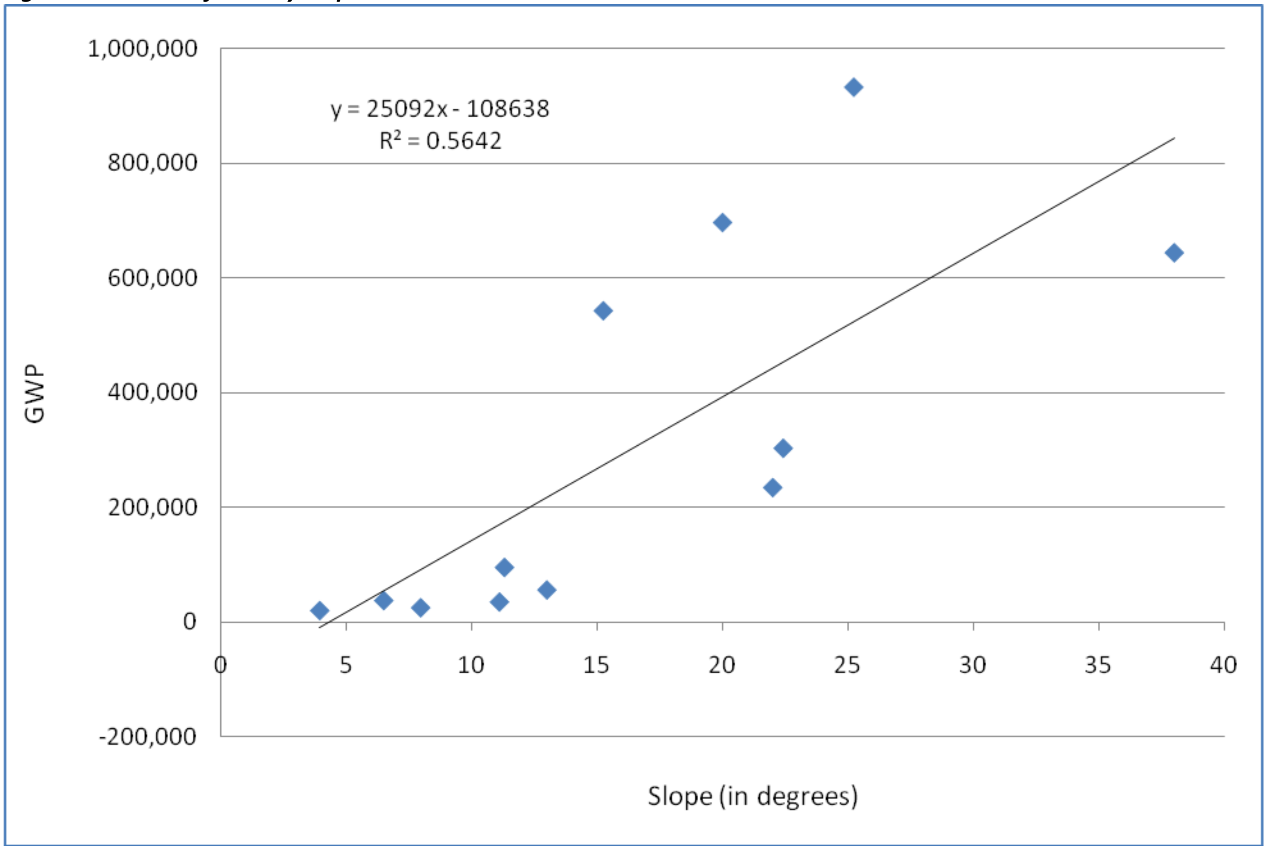


Figure 16 and 17 present the relationship between GWP and slope for clay and P sites. As indicated in both figures the relationship between GWP and slope, though positive, was less strong than the previous soil types (r = 0.32 and 0.23 respectively). The R^2 values indicate that only 10% and 0.5% of the variance in GWP (for clay and P sites) can be explained by the variation in slope. Of note, the data points are widely spread and this suggests the presence of one or more other factors (e.g. size of site) contributing to the variation in GWP results.

Figure 16 – GWP of clay by slopes

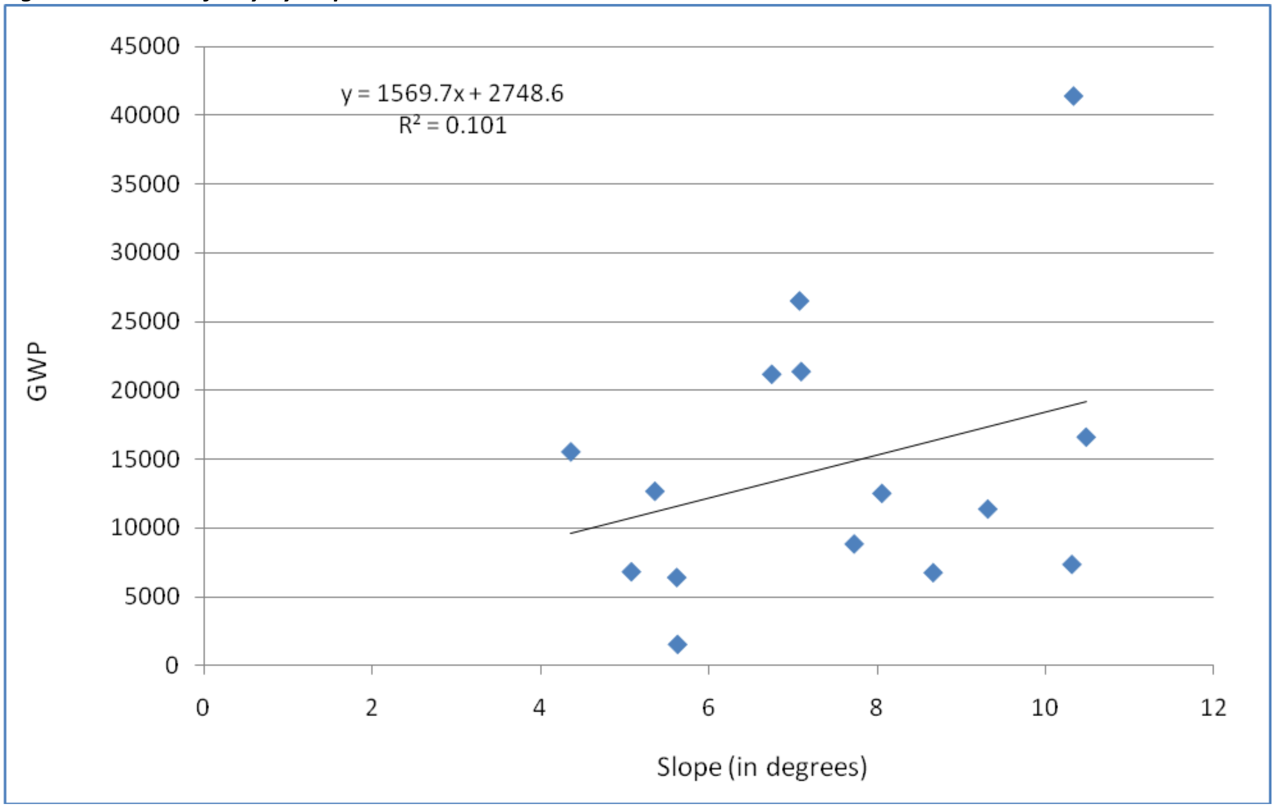
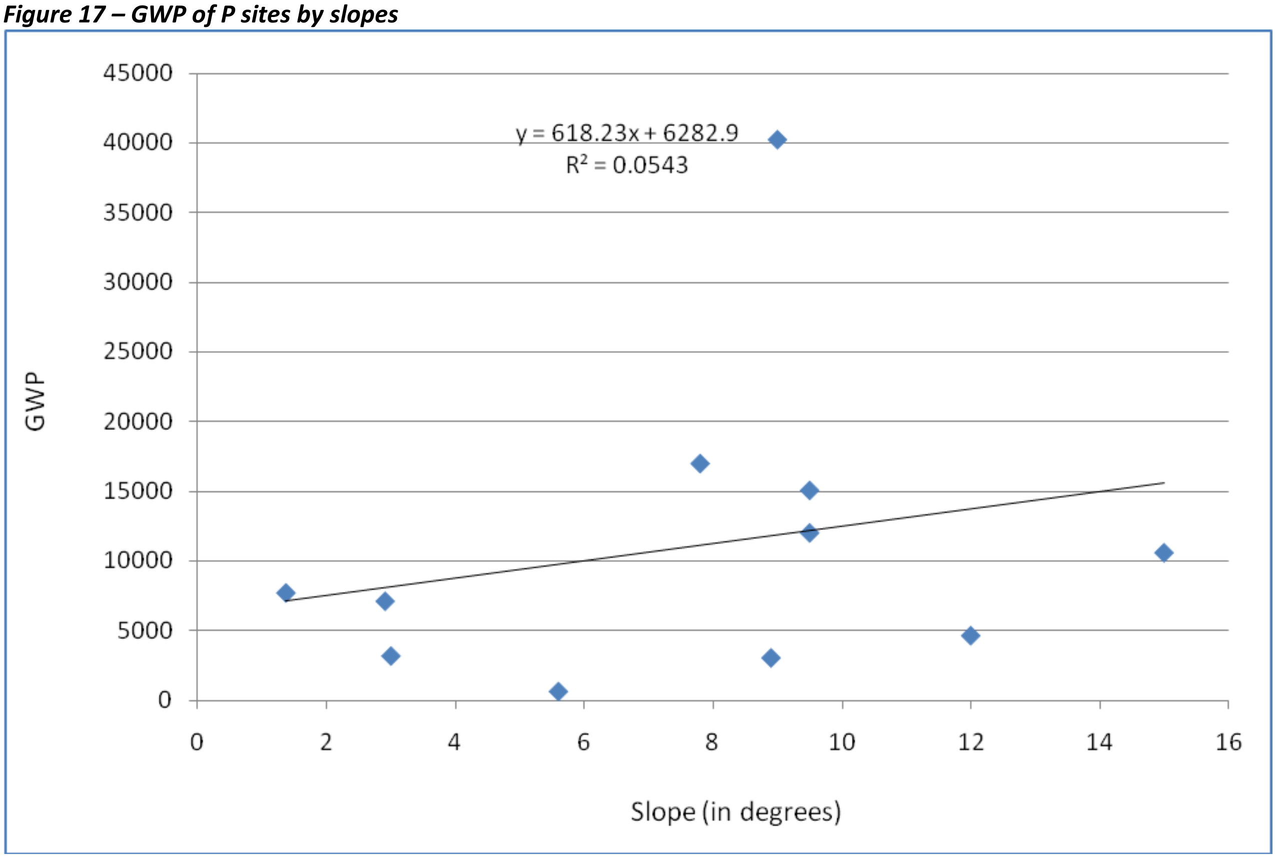


Figure 17 – GWP of P sites by slopes



7. LIFE CYCLE INTERPRETATION

The final phase of an LCA is interpretation, which includes evaluation of the data quality, and reports the final conclusions. Checks for completeness, sensitivity, and consistency to increase confidence in the reliability of the study. The final report should be unbiased with transparent discussion of assumption and approximations.

The various life cycle phases of construction on sloping sites have been assessed and modelled in the study. Computer software of Cost X and GaBi 4.4 were used in measuring material quantities and assessing environmental impacts. Supplementary information was also sourced from the literature and reports in the public domain. It is the intention for the research to ensure the data quality to be the highest for modelling environmental impacts of construction on sloping sites from the cradle-to-grave. The data includes both energy and material flows. Energy use in plant and equipment, and transport during construction are derived from literature sources and every effort has been used to ensure the quality and reliability of this data. Since it has been the minimal amount of activities during operation phase of the building's life cycle sensitivity analyse has little effect on the result and therefore has not been considered in the study.

8. CONCLUSIONS AND RECOMMENDATION

This study provides FWPA, designers and industry practitioners with an understanding on the environmental impact of cut and fill excavation construction on sloping sites. The study quantifies all the significant inputs and outputs to the cut and fill excavation, retaining wall and associated subsoil drainage works. The results indicate that slope has a positive correlation with both cumulative energy demand and greenhouse gas emissions (as measured using GWP). On sites conforming to this trend, rock has higher cumulative energy demand and higher greenhouse gas emissions than other soil types. The study also revealed that construction on very steeply sloping sites was often seen as unrealistic and impractical by those involved. This was apparent due to the scarcity of such sites found during the study (albeit that the study reviewed 122 sites in total) and by virtue of the comments made by those questioned during the data gathering process including volume builders, residential land developers and geo-technical engineers.

It was evident that a steep slope increases the burden substantially in cumulative energy demand and greenhouse gas emissions. Alternative solutions such as suspended flooring systems may minimise the disturbance to the land and natural habitat. Further research should develop and compare appropriate options with the results in this study. This should take into account balancing resource consumption and disturbance to the natural ground. In addition economic analysis – such as Life Cycle

Cost Analysis - may also be included as further research to assess the impact of various approaches of construction on sloping sites in balancing environmental protection and return on investment.

The study examines the cumulative energy demand and greenhouse gas emissions by the square metre for building footprint and gross floor area. The results reveal that building footprint is perhaps the most appropriate measure of the two because it more directly exposes the need to reduce the area of the building footprint in order to reduce cumulative energy demand and greenhouse gas emissions from cut and construction. Here, multi-level dwellings will perform better than single storey dwellings. However further research may also be required to assess the impact of building multi-levels in terms of resource consumption and environmental impact in conjunction with single level construction on sloping sites.

This study does not provide a proportional perspective concerning how much cut and fill excavation contributes to the overall LCA of an entire dwelling. This would provide a relative and contextual understanding of the findings presented in this report and would also be useful in providing a more holistic view of the cumulative energy demand and GHG associated with residential dwelling construction.

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Appendix A – Key information pertaining to projects sampled in the study

Project code	Slope	Site area (m^2)	Building footprint (m^2)	GFA (m^2)
A1 Little Bay	1:10	568	218	497
A2 Middleton Grange	1:10	285	76	154
A3 Middleton Grange	1:10	290	76	154
A4 Middleton Grange	1:10	380	113	190
A5 Middleton Grange	1:10	450	212	329
A6 Little Bay	1:6	661	242	480
A7 Bungendore	1:6	1211	334	668
A8 Little Bay	1:6	549	168	420
A9 Little Bay	1:4	535	347	560
A10 Little Bay	1:4	643	290	870
A11 Little Bay	1:4	814	408	1020
A12 Little Bay	1:4	736	259	777
A13 Little Bay	1:4	1049	254	781
A14 Little Bay	1:4	581	241	603
B1 Burradoo	1:10	1993	330	660
B2 Pendle Hill	1:10	576	187	330
B3 Helensburg	1:10	579	228	228
B4 Gillieston Height	1:10	745	215	215
B5 Moorebank	1:10	600	192	336
B6 Gillieston Height	1:6	680	232	232
B7 Casula	1:6	504	191	287
B8 Albion Park	1:6	746	271	413
B9 Flinders	1:6	667	179	322
B10 Fletcher	1:6	603	154	271
B11 Woomona	1:6	520	174	270

B12 Gillieston Height	1:6	638	216	216
B13 Woronora	1:4	877	171	295
B14 Flinders	1:4	928	194	359
B15 Fletcher	1:4	581	188	286
C1 Castle Hill	1:10	421	156	305
C2 Auburn	1:10	405	195	316
C3 Wilton	1:10	1000	352	704
C4 Gymea Bay	1:10	669	408	204
C5 Castle Hill	1:6	465	156	305
C6 Castle Hill	1:6	421	156	305
C7 Castle Hill	1:6	688	180	379
C8 Castle Hill	1:6	697	171	370
C9 Castle Hill	1:6	695	180	363
C10 Castle Hill	1:4	843	180	363
C11 Castle Hill	1:4	831	171	380
D1 Hornsby	1:10	542	152	256
D2 Figtree	1:6	694	199	323
D3 Wahroonga	1:6	422	154	154
D4 Figtree	1:4	742	146	239
D5 Newport	1:4	2061	279	689
D6 Newport	1:4	2166	290	471
D7 Palm Beach	1:2	1758	612	760
D8 Palm Beach	1:2	650	131	489
D9 Newport	1:2	855	143	402
D10 Palm Beach	1:2	1134	270	807
D11 Newport	1:2	723	151	453
D12 Bilgola	1:2	763	226	775
Note: **A = Sand B = Clay C = P D = Rock**				

Appendix B – Definitions of Soil Categories in Australian Standard AS 2870

Soil Classifications

A Most sand and rock sites with little or no ground movement from moisture changes

S Slightly reactive clay sites with only slight ground movement from moisture changes

M Moderately reactive clay or silt sites which can experience moderate ground movement from moisture changes

H Highly reactive clay sites which can experience high ground movement from moisture

E Extremely reactive clay sites which can experience extreme ground movement from moisture changes

P Sites which include soft soils, such as soft clay or silt or loose sands, landslip; mine subsidence; collapsing soils; subject to erosive reactive sites subject to abnormal moisture, conditions or sites which cannot be classified otherwise.

Appendix C – Global warming potential (GWP) of greenhouse gases

Name	Chemical formula	Global warming potential for 100 year
Carbon dioxide	CO_2	1
Methane	CH_4	21
Nitrous oxide	N_2O	310
HFC-23	CHF_3	11,700
HFC-32	CH_2F_2	650
HFC-41	CH_3F	150
HFC-43-10mee	$C_5H_2F_{10}$	1,300
HFC-125	C_2HF_5	2,800
HFC-134	$C_2H_2F_4(CHF_2CHF_2)$	1,000
HFC-134a	$C_2H_2F_4(CH_2FCF_3)$	1,300
HFC-143	$C_2H_3F_3(CHF_2CH_2F)$	300
HFC-143a	$C_2H_3F_3(CF_3CH_3)$	3,800
HFC-152a	$C_2H_4F_2(CH_3CHF_2)$	140
HFC-227ea	C_3HF_7	2,900
HFC-236fa	$C_3H_2F_6$	6.300
HFC-245ca	$C_3H_3F_5$	560
HFE-7100	$C_4F_9OCH_3$	500
HFE-7200	$C_4F_9OC_2H_5$	100
Perfluoromethane	CF_4	6,500
Perfluoroethane	C_2F_6	9,200
Perfluoropropane	C_3F_8	7,000
Perfluorobutane	C_4F_{10}	7,000
Perfluorocyclobutane	$c\text{-}C_4F_8$	8,700
Perfluoropentane	C_5F_{12}	7,500
Perfluorohexane	C_6F_{14}	7,400
Sulphur hexafluoride	SF_6	23,900

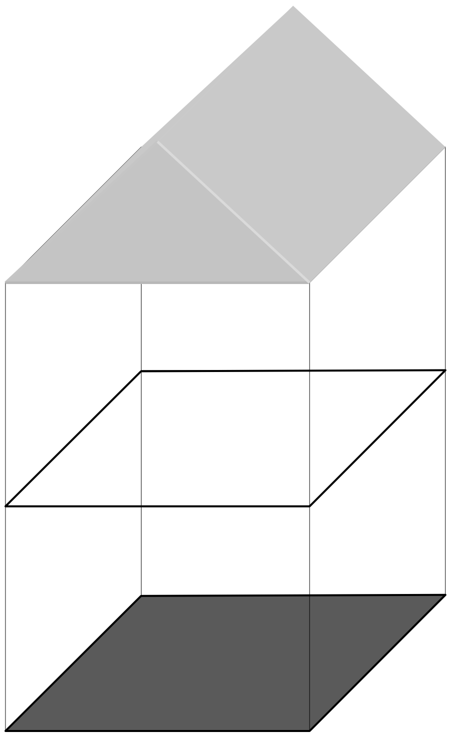
Source: IPCC (1995)

Appendix D – Inputs and outputs for the cut and fill construction

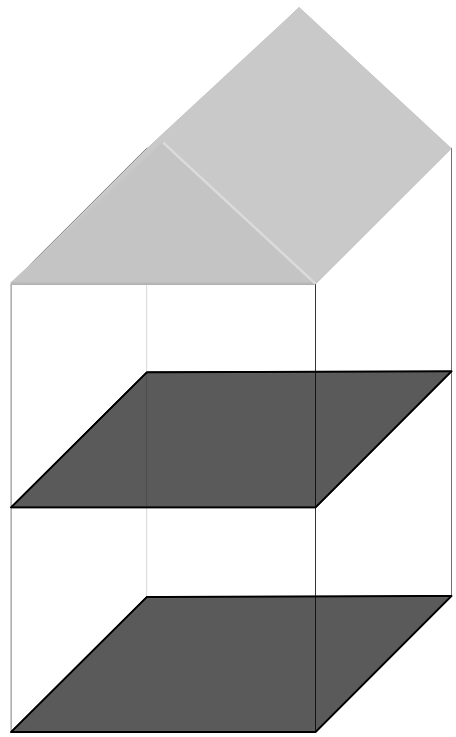
Flow	Unit	Amount
Inputs		
Excavator for cut & fill activities on site	Litre/hr	15 litres/hr (output rate vary to soil and slope type)
Transport excess excavated materials to landfill (11m^3 truck), travel distance vary from 4 to 29 km	Litre/km	40 litres/1000kms
Filling material	t	Various (refer to Table 2)
Transport filling material to site (11m^3 truck), travel distance vary from 6 to 36 km	Litre/km	40 litres/1000kms
Block retaining wall (10m^2)		
Concrete block	kg	2808
Cement	kg	1104
Sand	kg	2747
Aggregate	kg	3969
Lime	kg	92
Steel	kg	115
Water	kg	672
Treated timber retaining wall (10m^2)		
Treated timber	kg	705
Cement	kg	269
Sand	kg	673
Aggregate	kg	1279
Blue metal	kg	118
Water	kg	193
Structural steel & treated timber retaining wall (10m^2)		
Steel	kg	151
Treated timber	kg	276
Cement	kg	307
Sand	kg	769

Aggregate	kg	1461
Water	kg	221
Subsoil drainage (based on 10m^2 retaining wall)		
PVC pipe	kg	20
Blue metal	kg	4054
Geofabric	kg	2
Outputs		
Levelled cut & fill platform	m^2	1
Retaining wall	m^2	10
Subsoil drainage	m^2	10
Cumulative energy	m^2	Various depending on soil and slope type (refer to Table 5)
GWP	kgCO_2-e/m^2	Various depending on soil and slope type (refer to Table 6)

Appendix E – Depiction of the comparative difference between BF and GFA



Building footprint (BF) shown in Grey



Gross Floor Area (GFA) shown in Grey