LIFE CYCLE ASSESSMENT: REUSABLE AND DISPOSABLE NAPPIES IN AUSTRALIA

Kate O'Brien, Rachel Olive, Yu-Chieh Hsu, Luke Morris, Richard Bell and Nick Kendall

Environmental Engineering, School of Engineering,
The University of Queensland, Brisbane

URL: http://www.eng.uq.edu.au/environmental/

Email: k.obrien@uq.edu.au

ABSTRACT

Australian data were used here in a life cycle assessment of three types of nappies (disposable, home-washed re-usable, and commercially-washed reusable). Four environmental indicators were used: water resource depletion, non-renewable energy depletion, solid waste and land area for resource production. For the first time, the effect of forestry on runoff was included in water resource depletion. A range of scenarios were considered for each nappy, to account for variability in usage rates and washing practices. The results enable parents to assess the impact of each nappy system based on their own conditions. Comparing variation within and between nappy systems also allowed a fairer assessment of the nappy systems. Home-washed reusable nappies washed in cold water in a front-loading washing machine and line-dried were found to use less energy and land resources, comparable water resources, and produce similar or lower quantities of solid waste, compared to the other nappy systems. Methods to reduce the impact of each nappy system were identified. The major difference between the nappy systems is that the user has much more control over the environmental impact of home-washed reusables. The main role by which consumers can reduce the impact of commercially-washed and disposable nappies is to use them less frequently. The study highlights the importance of including variability explicitly in the inventory analysis. The results also suggest that accounting for reduced forestry runoff in water resource depletion may impact the outcome of studies involving softwood-sourced products; further work is required to better quantify the effect of forestry on water resources.

Keywords: nappies, life cycle assessment, energy, water

1. BACKGROUND

Most babies in Australia wear nappies until they become toilet trained, usually somewhere between 2 and 3 years of age. Traditionally babies wore reusable (cloth) nappies, which were washed after use, either within the home or in a commercial laundry. However 95% of babies in Australia currently wear disposable nappies [1], which are disposed of after a single use. There has been vigorous debate in the community about which nappy system is more sustainable, and a number of life cycle studies have been conducted on this topic [2-5]. However the variability in usage rates and washing practices between families, and the different environmental impacts of disposable and reusable nappies, has made this comparison difficult. Most of the previous studies [2-4] compared nappy systems on the basis of average practices, hence could not identify the system with the potential for the least impact.

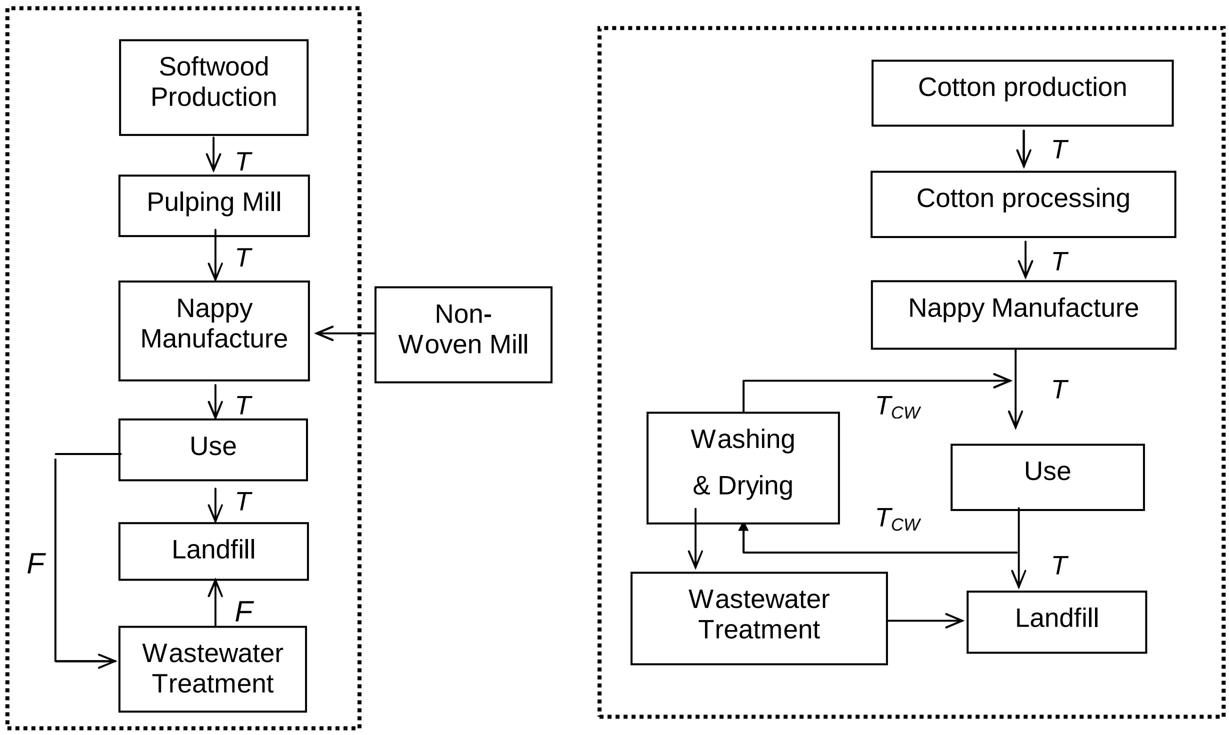
Variability is addressed explicitly in this study, which quantifies the impact of reusable (home- and commercially-washed) and disposable nappies in Australia. The main sources of variability (usage rates and washing practices) are addressed separately, and all results are reported in terms of a range of values. The results of this study thus enable parents to assess the impact of each nappy system based on their own conditions (e.g. number of nappies changed per day). This approach also means that the nappy system with the potential for least impact can be identified, along with the conditions which minimise impact. Furthermore, directly incorporating variability in the calculations allows a fairer comparison of the nappies, because the results are less dependent on single assumptions.

This study also includes some aspects of the disposable nappy life cycle which have not been investigated previously. For example, while previous studies [2-5] have included water consumed in the irrigation of cotton in the life cycle of reusable nappies, here the water resource depletion associated with reduced runoff in forestry plantations [6-9] is included for the first time in the disposable nappy life cycle. Two different scenarios for the disposal of faeces from disposable nappies are examined; flushing into the sewage system, and disposal with the nappy in municipal waste.

2. SCOPE

Figure 1 shows a simple process flow diagram for the life cycle of nappies. The study includes disposable nappies, manufactured using softwood pulp and plastics and disposed of in landfill, and reusable nappies, made from terry towelling cotton. Four nappy systems were considered:

- **Disposable – direct disposal**, where the nappy and its entire contents are placed in the garbage after use;
- **Disposable – flushed**, where the faeces is flushed into the sewer system before the nappy is placed in the garbage;
- **Reusable – home-washed**, where nappies are washed and re-used within the home;
- **Reusable – commercially-washed**, where nappies are washed in a commercial laundry.



a) Disposable nappies **b) Reusable nappies**

Fig 1. Life cycle of a) disposable and b) reusable nappies; dashed line indicates the system boundary, *T* indicates transport, T_{CW} indicates transport for commercially-washed nappies only, and *F* indicates a process only relevant to the disposable-flushed system

Alternative nappy materials (such as hemp and bamboo) and compostable nappies were not considered. While elasticated and shaped nappies were not included in the study, the impact of these nappies may be calculated from the reusable data, adjusted for mass of cotton. Energy used in retail stores, travel to purchase nappies, production of wipes, creams and liners were excluded from the study. The production of components of disposable nappies other than pulp, and the production of nappy sanitizer and washing soaps/detergents were not included. Sludge from wastewater treatment plants was assumed to be landfilled (Fig. 1), but the treatment of leachate from landfill was neglected. Reusable nappies were assumed to be used within the household as rags after their life as nappies, and not landfilled. Where waste materials were composted or recycled, they were not considered as solid waste.

3. METHODOLOGY

Four environmental indicators were quantified for each nappy system: water resource depletion, energy consumption (renewable and non-renewable), solid waste and land area for resource production (cotton for reusable nappies, softwood for disposable nappies). A basis of 2.5 year was used [4], i.e. the environmental indicators were quantified for each nappy system over the first 2.5 years of a child's life. Data was determined primarily from Australian sources, using literature and information from manufacturers and suppliers.

Assumptions can have a large effect on any life cycle study. In particular, the results of nappy studies are strongly dependent on the number of nappies used per day, and the washing and drying practices for home-washed reusables [3,5]. This issue was addressed by calculating impacts over a range of usage rates, for two different washing machines. This allowed a fair and transparent comparison of all four nappy systems, and provides data which families can use to assess their individual impact.

3.1 Variability in usage rates

Three different usage scenarios were defined for each nappy type (Table 1-2). These scenarios accounted for the lowest and highest realistic values of nappy weights and usage rates (and nappy lifespan in the case of commercially-washed reusables). The low impact scenario combined the lowest impact values for each of these variables, and similarly the high impact scenario combined the highest impact values. The moderate impact considered average or typical values. The environmental indicators were calculated for each of the scenarios, for each nappy system.

	Low impact	Moderate impact	High impact
Mass per nappy	45 g	50 g	55 g
No. of nappy changes per day	4.2	5.5	7
Total mass of nappies over 2.5 years	173 kg	251 kg	352 kg

Table 1. Usage scenarios for disposable nappies

	Low impact	Moderate impact	High impact
Mass per nappy	100 g	125 g	150 g
No. of nappy changes per day	5	7	9
No. of nappies purchased [hw]	24	36	48
Number of washes before disposal [cw]	100	80	60
Total mass of nappies over 2.5 years	2.4 kg [hw] 4.6 kg [cw]	4.5 kg [hw] 10.0 kg [cw]	7.2 kg [hw] 20.5 kg [cw]

Table 2. Usage scenarios for reusable nappies; [hw] indicates data for home-washed nappies, [cw] indicates data for commercially-washed nappies

The average mass of disposable nappies was 50 g (Table 1). This was calculated by weighing samples of boys' and girls' disposable nappies for each size class (Newborn, Infant, etc.), and integrating over 2.5 years based on the average time spent in each size class, which was a function of recommended weight range for each size class, and child growth rates [10,11]. Disposable nappy mass was assumed to vary from this value by ±10%, to account for variability between brands and in the size of the child. The mass of reusable nappies (Table 2) was determined by weighing a number of brands of home-washed and commercially-washed reusable nappies.

The number of nappies used per day will vary between families and babies, and with the age of the child. This variation was captured in the study (Tables 1-2) through considering a range of usage rates, each averaged over the 2.5 year life cycle. More reusable nappies were assumed to be used per day than disposable nappies, due to the nature of the nappies.

3.2 Variability in washing practices for home-washed reusable nappies

Previous studies have generally applied "average values" for washing and drying practices for home-washed reusable nappies, for example assuming a certain percentage of nappies were tumble-dried [2-4]. While using average values enables calculation of the overall impact of an average population of nappy users, it does not allow identification of the system with the potential for the lowest impact, which was the purpose of this study. Here we have assumed a "best practice" washing and drying regime for home-washed reusable nappies, based on Australian conditions:

- Soiled (faeces-contaminated) nappies stored in a bucket (dry-pailed), and faeces flushed from the nappies once per day (6 L);
- Soiled nappies soaked in warm water (7 L) with nappy sanitiser every second day;
- All nappies (both wet and soaked soiled nappies) washed every second day;
- Washing water unheated (i.e. cold wash), and all nappies line-dried.

This represents average washing practice over the 2.5 year life cycle, which varies slightly with the age of the baby. Soaking was assumed to be in warm water, as specified in nappy sanitiser instructions. Energy required to heat water for soaking was 0.146 MJ L^{-1}, which was the energy required to heat water from 20 ^oC to 55 ^oC. The water heater was assumed to use non-renewable energy, such as gas or coal-fired electricity. The instructions on nappy sanitisers indicate that rinsing only was required after soaking, however we have assumed that all nappies were machine-washed after soaking, because that was more consistent with common practice in Australia. Wash temperature was assumed to be cold, because the nappy sanitiser did not specify that rinse water should be warm. All nappies were assumed to be line-dried to reduce energy usage. Line-drying is feasible in most parts of Australia.

Two different washing machines were considered; a water- and energy-efficient front loading machine (50 L of water and 50 Wh per load), and a less efficient top-loading machine (150 L of water and 150 Wh per load). While most washing machine manufacturers report water and energy consumption only as annual averages, these values were from direct measurements of the water (reported in Ref. [12]) and energy [13] consumed per load for a range of washing machines available in Australia. The energy consumption was much lower than in previous studies [2-5], because only cold washing was considered.

3.3 Excreta and wastewater treatment data

An average of 1.4 stools per day, and a total of 91 kg of faeces and 458 kg of urine over the first 2.5 years of life was calculated from the Geigy tables [10,11]. This corresponds to a biological oxygen demand (BOD) load of 10.7 kg [11,14]. All of the BOD load was assumed to be associated with the faeces, and 54% of the BOD load was assumed to be removed from the wastewater treatment as sludge [15], 85% of which was landfilled [16], as indicated in Fig. 1. Energy consumption for wastewater treatment was 0.42 kWh m^{-3} [17].

3.4 Transportation data

Energy to transport freight was assumed to be 0.8 MJ diesel per tonne km for articulated trucks, and 0.168 MJ diesel per tonne km for shipping (calculated from Refs [18-19]). Garbage collection required 1 L of diesel per tonne of garbage, which accounted for the use of both garbage only and combined garbage and recycling trucks in Brisbane (calculated from Refs [20-22]).

3.5 Disposable nappy data

Disposable nappies were composed of 40% cellulose (pulp) [11,23]. The land area for forestry was calculated assuming that each kg of pulp requires 4.4 kg of woodchips [24], with a yield of 15 m^3 softwood per hectare per year [25], at a density of 500 kgm^{-3}.

Forestry is not irrigated, so previous studies have neglected water consumption in softwood production [2-5]. However pine forest plantations in Australia have reduced runoff compared to agricultural/pastoral land and native forests [6-9]. Replacing crops or grasslands with pine forest reduces annual runoff by as much as 200 mm [6-9]. Replacing native forest with pine plantations initially leads to an increase in runoff [7], but results in an overall runoff reduction of 50-100 mm once the forest is established [6-9]. Less runoff corresponds to lower stream flows, which can be detrimental to freshwater ecosystems and reduce water available for human usage. However it is very difficult to quantify this effect. Annual rainfall, soil types, percentage of catchment afforested, the age of pine plantation and the nature of the vegetation replaced all affect runoff reduction, which is also affected by inter-annual variations in rainfall [6-7]. Furthermore, plantations may also significantly increase groundwater uptake if replacing shallow-rooted vegetation [7].

Here we assumed that softwood production corresponds to a reduction in runoff of 75 mm, i.e. 750 m^3 (0.75 ML) per hectare. This represents a value in the lower range of predicted runoff reduction [6-9]. If this value markedly effects the water consumed over the life cycle of disposable nappies, it will indicate that runoff reduction needs to be considered in the life cycle of softwood products, and hence that more research is required to better quantify this effect.

Energy consumption in softwood production was 0.23 MJ per kg of woodchip (calculated from Foran et al. [26]). For each kg of pulp produced, 0.065 m^3 of water, 15.8 MJ of steam energy, 4.2 MJ of electrical energy and 14.2 MJ of natural gas were used, and 0.0024 kg of landfill waste produced [27]. 0.027 m^3 of wastewater was also produced per kg of pulp [24].

Nappy production used 0.44 L of water, 0.18 MJ of gas energy, 2.4 MJ of electrical energy, and produced 0.045 kg of solid waste and 0.44 L of wastewater, per kg of nappies produced [4].

Transportation energy was calculated per unit mass for articulated trucks from softwood source to pulping mill (70 km) and pulping mill to nappy production (1300 km). Energy to transport nappies from producer to retail (1000 km), was calculated per unit volume, assuming an average semitrailer volume of 168 m^3, with fuel efficiency 0.51 L km^{-1} [28], and an average volume of 2.72 x 10^{-4} m^3 per nappy (determined by measuring the packaging of nappies across the size categories, and integrating these over the typical growth of Australian children in their first 2.5 years [11]).

Under the “direct disposal” scenario, all urine, faeces and nappies were landfilled; under the “flushing” scenario, 6 L water was used to flush faeces from each soiled nappy, and all faeces was assumed to enter the sewage system.

3.6 Reusable nappy data

All reusable nappies were assumed to be terry-towelling, manufactured in Asia from cotton grown in Australia. An average yield of 1806 kg per hectare [29] was used to determine land area for cotton growth over the life cycle of reusable nappies. Water for cotton growth was 12 ML per hectare [29], including irrigation and uptake of soil moisture and rainfall. Energy consumed during cotton growth and production of cotton towelling used in nappies was 98.1MJ kg^{-1} [30]. Water consumption during nappy production was 0.018 m^3 kg^{-1}, and solid waste production was 1.28 kg per kg of nappies [4].

Transportation energy was calculated assuming that 40% of material transported to the gin was cotton [31], and that cotton was transported 3 km from field to gin, 300 km from gin to port, and 100 km from port to retail by articulated truck. Transport of cotton to and from Australia for milling and nappy manufacturing involved a return ship journey of 10 000 km.

Pilchers (plastic pants) were assumed to be used with all reusable nappies, with a total mass of 0.464 kg over the life cycle. This corresponded to 7 MJ of energy, 0.6 m^3 of water used and 0.02 kg of solid waste generated during production [11].

3.7 Commercially-washed reusable nappy data

Water and energy consumption in the commercial laundry were assumed to be 1.17 L and 14 kJ per nappy respectively. These values were calculated from data from a commercial nappy laundry [32], where the washing cycle involved a 10 minute wash at 65 ^{o}C, a 12 minute wash at 80-85 ^{o}C, an 8 minute bleach cycle, three rinses and hot air drying.

This washing regime was quite different to that of the home-washed reusables, which were assumed to be washed in cold water and line-dried. This reflects the different nature of home-washed and commercially-washing reusables. Line-drying may not be practical in a commercial laundry, and while home-washed nappies are worn by the same child or children within one household, commercially-washed nappies are returned to children in different households and/or child-care centres. This means that commercially-washed nappies require a more stringent washing regime to prevent any possible transfer of disease between users. Furthermore, marks or stains may be accepted on nappies washed in a home environment, but appearance is more important for nappies supplied by a commercial laundry.

The importance of appearance of commercially-washed reusables also explains the shorter life-span of these nappies: 60-80 [33] to 100 washes [4]. In contrast, home-washed reusables are assumed to last for the full 2.5 years [4], i.e. approximately 200 washes (Table 3).

Transportation of commercially-washed nappies between users and the laundry used an average of 0.006 L per nappy in Brisbane [34]. This was double the value used in Ref. [4], which reflects the lower urban density in Australia compared to the UK. It was assumed that diesel fuel was used to transport the commercial nappies, with an energy density of 38.6 MJ L^{-1} [19].

4. RESULTS

4.1 Water resource depletion

There was overlap between the water resource depletion determined for each nappy type (Figure 2a, Tables 3-4), except that reusable nappies washed in a top-loading washing machine were found to use more water than disposable nappies or reusable nappies washed in a more efficient front-loading machine, regardless of the number or mass of the nappies used.

The range of water depletion calculated over the life cycle of commercially-washed reusables overlapped with the values for home-washed reusables, but had much greater variability. Whereas washing (including soaking and flushing) accounts for 40-80% of total water consumed by home-washed nappies, it only accounts for 7-15% of water consumed by commercially-washed nappies, as the commercial washing process is more water-efficient (Table 4). However the shorter lifespan of commercially-washed reusables means that more cotton is required over the life cycle (Table 2), and hence water depletion associated with nappy production is higher (Table 4).

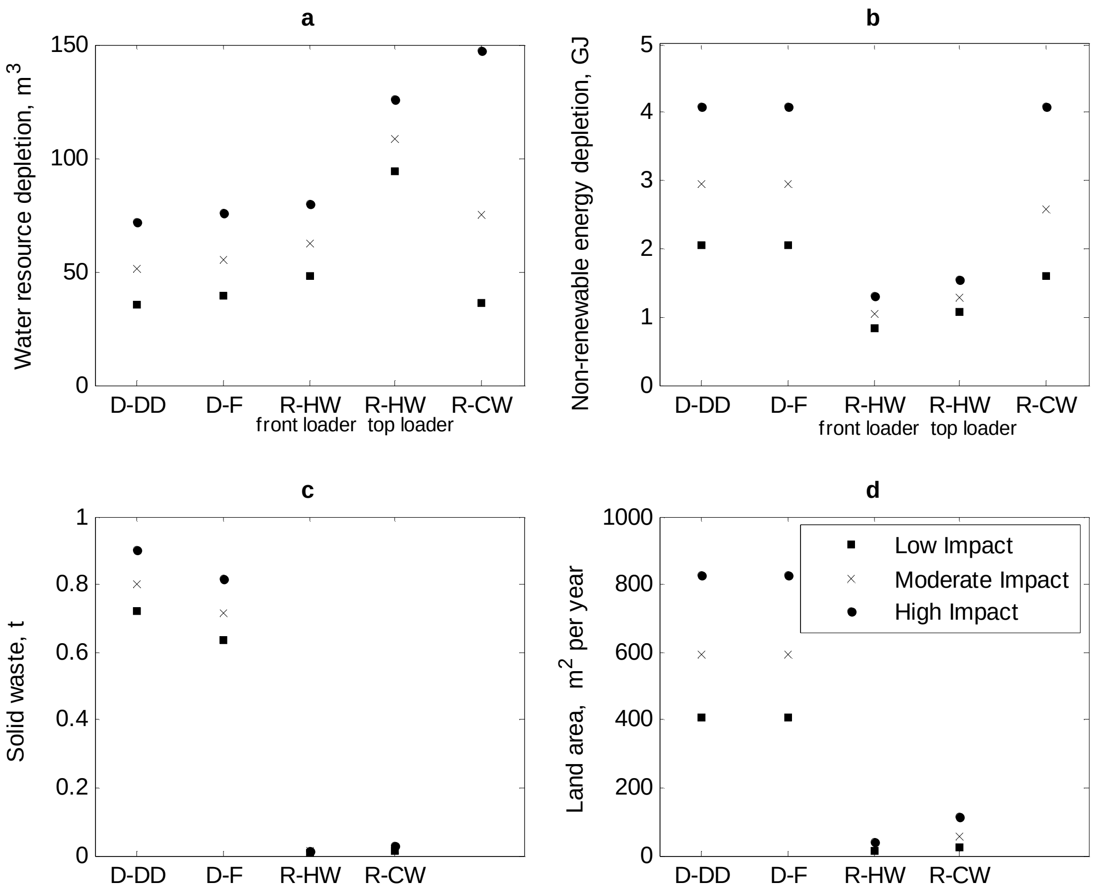


Figure 2. Resource impacts of each nappy system DD-D Disposable - direct disposal of faeces; DD-F Disposable – faeces flushed; R-HW home-washed reusables; R-CW commercially-washed reusables: a) water resource depletion; b) non-renewable energy depletion; c) Solid waste; d) land area required for resource production

	Water resource depletion m^3	Energy consumption MJ	Solid waste kg
Softwood production	31 – 62	70 – 140	NA
Pulp production	4.5 – 9.2	1090 -2220* (steam) 290- 590 (electricity) 980 -2000 (natural gas)	0.2-0.3
Nappy production	0.08 – 0.15	420 – 850 (electricity) 30 – 60 (natural gas)	<0.1
Nappy transport	NA	210 – 390	NA
Wastewater treatment	3.9^{f}	$3 – 6^{dd}$ $9 – 12^{f}$	5^{f}
Municipal waste	**NA**	$45 – 56^{dd}$ $39 – 50^{f}$	$722 - 901^{dd}$ $631 - 810^{f}$
TOTAL	**35 – 71 $m^{3\ dd}$** **39 – 75 $m^{3\ f}$**	**3.1-6.3 GJ** **2.0-4.1 GJ non-renewable**	**0.72 – 0.90 t** **0.64 – 0.82 t**

Table 3. Range of water resource depletion and energy consumption and solid waste produced over the life cycle of disposable nappies; ^{dd} indicates data only relevant to Direct Disposal scenario; ^{f} indicates data only relevant for the Flushing scenario (where faeces are disposed of through the sewage system); * indicates renewable energy; NA indicates not applicable, or negligible

	Water resource depletion m^3		Energy consumption MJ		Solid waste kg	
	HW	**CW**	**HW**	**CW**	**HW**	**CW**
Cotton growing	16-48	30-137	81-244^{e} 137-412^{nr} 17-50^{o}	155-700^{e} 260-1180^{nr} 30-110^{o}		
Cotton processing & nappy production	0	0			3 - 9	5.6 – 25.4
Pilcher pant production	0.60	0.60	7	7	0.02	0.02
Flushing	5	NA	NA	NA	NA	NA
Soaking	3	NA	468	468	NA	NA
Washing	23 ^{fl} 68^{tl}	5-10	82 ^{frontload} 247 ^{topload}	66-120	NA	NA
Wastewater treatment	NA	NA	35 ^{frontload} 103 ^{topload}	8-15	NA	5
Muncipal waste	NA	NA	0	0	5	0.5
Nappy transport	NA	NA	5-14	9-40	NA	NA
Nappy delivery	NA	NA	NA	1060-1900	NA	NA
TOTAL	**48-80 $m^{3\,fl}$ 94-126 $m^{3\,tl}$**	**36-147 m^3**	**0.83-1.3 GJ ^{fl} 1.1 -1.55 GJ ^{tl}**	**1.6-4.1 GJ**	**8-14 kg**	**11 –31 kg**

Table 4. Range of water resource depletion and energy consumption and solid waste produced over the life cycle of home-washed ("HW") and commercially-washed ("CW") reusable nappies: ^{fl} indicates front-loading washing machine used, ^{tl} indicates top-loading washing machine used,^{e} indicates electrical energy, ^{nr} indicates fossil fuels, ^{o} indicates other energy source; NA indicates not applicable, or negligible

The water resource depletion calculated here for disposable nappies (Figure 2a, Table 3) was much higher than in previous studies [2-4], except where hydroelectricity water requirements and power station cooling water have also been included [5]. This is because we included the impact of forestry on runoff, in addition to the water consumed in other parts of the disposable nappy life cycle. While there was some overlap in the ranges reported here, water resource depletion associated with the softwood production for disposable nappies (Table 3) was higher than for the cotton growing stage of home-washed nappies (Table 4). This is despite the fact that forestry is typically much less water intensive (on a per-area basis) than cotton growing – indicating that it was the much larger mass of raw material required for the production of disposable nappies over the 2.5 year lifecycle that was the driver for this result. This difference in raw material requirements is also reflected in the land use for each nappy system (Figure 2d, Section 4.4). However, as explained in Sec.3.5, the impact of forestry on runoff is difficult to quantify, due to high variability arising from local factors such as rainfall.

4.2 Energy resource depletion

Home-washed reusable nappies were found to use less non-renewable and total energy over the life cycle than any other nappy system (Figure 2b), regardless of the number of nappies used, the mass of nappies, or the type of washing machine. While the type of washing machine affects the total energy required for home-washed reusables, this difference is small compared to the difference between nappy systems (Figure 2b, Tables 3-4). The type of washing machine had a bigger effect on water resource depletion than on energy depletion for home-washed reusables (Figure 2a-b). This is because washing contributes more to total water consumption (29-73%) than to total energy consumption (10-41%), in coldwater washing. Heating water for soaking nappies consumes 30-56% of the energy used over the life cycle of home-washed reusables (Table 4); hence using solar water heating could substantially reduce the non-renewable resource depletion associated with these nappies. More energy is, and hence more greenhouse gas emissions generated, if the nappies are tumble-dried or washed in hot water, particularly if a solar hot water system is not used [2-5].

The range of non-renewable energy depletion reported across all scenarios was similar over the life cycle of disposable and commercially-washed reusable nappies. Pulp production is responsible for 75% of the non-renewable energy required over the life-cycle of disposable nappies, even though 46% of energy used in pulping is renewable (steam generated from spent liquor in the pulping plant, Table 3). In contrast, 52-62% of the total energy over the life cycle of the commercially-washed nappies is the energy required to transport the nappies between users and the laundry (Table 4). This is the only significant transport step in any of the nappy life cycles. Shipping cotton overseas for processing represents only 1-2% of the total energy over the life cycle of reusable nappies, since the total mass of cotton required is small (Table 2). Even though a large mass of disposable nappies is used (Table 1), transport of disposable nappies still only represents 6-7% of the total energy over the life cycle (and 9-11% of non-renewable energy), more than half of which is due to transport of the nappies to retail stores (1000 km).

4.3 Solid waste

Solid waste produced over the disposable nappy life cycle was found to be more than 20 times the solid waste associated with home-washed and commercially-washed reusable nappies (Figure 2c, Tables 3-4). Urine (458 kg) accounts for more half of the mass of solid waste generated by disposable nappies, and the mass of the nappies (173-352 kg, Table 1) is the other major contribution to solid waste. Flushing the faeces down the toilet (disposable – flushing scenario) reduces the mass of solid waste by 86 kg, but increases water consumption by 3.9 m^3 over the life cycle of disposable nappies (Table 3). If disposable nappies could be composted, the mass of solid waste could be substantially reduced, although for hygiene reasons faeces-contaminated nappies could not be composted.

Light et al. [35] have proposed that disposable nappies do not affect landfill volume, based on experiments which found that disposable nappies do not affect compression of municipal waste where they represent less than 10% of total volume. Since a large number of nappies are likely to enter the garbage trucks from a few homes where babies live, it is unlikely that disposable nappies will be uniformly distributed throughout the garbage; hence it is still important to consider total mass of solid waste.

4.4 Land area for raw material production

Disposable nappies were calculated to use substantially more land for resource production than required by reusable nappies (Figure 2d, Table 5). While cotton yield per hectare is typically less than softwood yield [25, 29], the greater mass of material required for disposable nappies (Tables 1-2) mean than more land is required overall.

Based on the assumptions in this study, commercially-washed nappies require 2-3 times the land area of home-washed nappies (Figure 2d, Table 5). This is due to a larger mass of cotton required for commercially-washed nappies (Table 2), due to their shorter lifespan.

	Disposable – direct disposal	Reusable – Home-washed	Reusable – Commercially-washed
Land area, m^2 per year	407-829	13-40	25-114

Table 5. Land area for production of raw materials over the life cycle of each nappy type

4.5 Comparison of nappy systems

More than 90% of water and energy consumption and land use occurs during the pre-use stage of the disposable nappy life cycle (softwood production, pulping and nappy production). For reusable nappies, both resource production and washing are important, and transport is a significant source of energy consumption for commercially-washed nappies.

In the impact categories considered here, home-washed reusable nappies washed in cold water in a front-loading washing machine and line-dried have the potential to have a lower environmental impact than either disposable nappies or commercially-washed reusable nappies. Under these conditions, home-washed reusable nappies produce less solid waste, and use less land area and energy (both total and non-renewable) than disposable nappies across all impact scenarios. The range of water resource depletion is similar for both nappy systems (Figure 2); however there is large uncertainty in the estimate of water resource depletion associated with softwood production.

While land area and solid waste impacts were similar for all reusables, and the range of water usage for home-washed nappies fell within the range for commercially-washed nappies, home-washed nappies use less energy than commercially-washed nappies, and hence have the potential for lower environmental impact overall.

When compared with disposable nappies, commercially-washed reusables were found to produce less solid waste, require less land area for raw material production, and require very similar amounts of energy. The range of water depletion calculated for commercially-washed nappies encompassed the range determined for disposables. Hence the relative impacts of commercially-washed and disposable nappies will depend on usage rates, nappy mass and nappy life-span. For example, low impact commercially-washed nappies may have less impact than moderate or high impact disposables. Comparing moderate or high impact commercially-washed reusables with low impact disposables is more difficult, because the former depletes greater water and energy resources, while the latter generates more solid waste and requires more land area for raw material production. This comparison is further complicated by the uncertainty in water associated with softwood production. In addition, our study only considered data from only one disposable nappy manufacturer and one commercial nappy supplier. Variation in efficiencies and processes between companies may be significant, and hence affect this comparison.

In this study, commercially-washed nappies had a very wide range of values for resource depletion (particularly water). This is because three usage parameters were varied for commercially-washed reusables (nappy mass, number of changes per day and lifespan), while only two parameters (nappy mass and number of changes per day) were varied for each of the other nappy systems. The primary way to reduce the impact of commercially-washed reusables is to reduce the amount of cotton used, which is determined by the number of changes per day, and the mass and lifespan of the nappies. The number of nappies used per day is generally determined by the frequency and volume of the babies' excreta. However the mass and the lifespan of the nappy can be adjusted. Commercially-washed nappies have a lifespan of only 60-100 washes, compared to approximately 200 washes for home-washed nappies (Table 2). This is because stains and discoloration which may be acceptable in a home environment are not acceptable for a commercially operation, where nappies are taken to many different families and/or childcare centres.

The "flush" and "direct" disposal disposable nappy systems both require the same land area and similar energy resources, but flushing the faeces increases water consumption and reduces solid waste. However the differences between the two disposal scenarios are very small (Table 3).

5. CONCLUSIONS

Overall, based on the four environmental indicators used in this study, home-washed reusable nappies have the potential for the least environmental impact if washed in a water-efficient front-loading washing machine in cold water, and line-dried. While there was significant variability within each nappy system, due to variation in mass of nappies, usage rates and nappy lifespan, the impacts of reusable nappies home-washed under these conditions were less than, or similar, to the other nappy systems in all four impact categories.

The major difference between the three nappy types is that the user has much more control over the environmental impact of home-washed reusables. In contrast, all four environmental indicators occur largely outside the control of the user for disposables and commercially-washed reusables. The only method by which users can reduce the impact of these nappies is to use less of them (e.g. nappy-free time for the baby), and the largest potential reductions lie with reducing the impacts before and after use.

There are a number of ways in which users can reduce the impact of home-washed nappies, below the levels quantified in this study. For example, using a solar hot water system to heat water for soaking soiled nappies would significantly reduce non-renewable energy depletion associated with washing reusable nappies. Using nappies requiring less cotton (e.g. elasticated or shaped nappies) would reduce the water resource depletion associated with cotton production, as would using nappies for more than one child [5], i.e. more than 2.5 years. Recycling water within the home (e.g. soaking the nappies in water collected from the shower/bath) can also reduce water resource depletion. A home-washing system may displace the need for other water and energy consumption associated with babies and nappies. For example, soiled clothing and cloths (a common side-effect of changing nappies) can be soaked and washed with nappies without additional water and energy usage. Baby wipes represent a credit opportunity of even greater significance; disposable nappy users generally purchase disposable baby wipes for cleaning the baby when nappies are changed. For users of home-washed reusable nappies however, rags or old nappies soaked in water can displace baby wipes with no additional environmental burden, since they can be soaked and washed with the nappies.

A range of possibilities exist for reducing the impacts of disposable nappies prior to and after use. Reducing nappy mass reduces impacts almost proportionally [5]. Reducing water and energy consumption during pulping should be done where possible, but the largest scope for improvements probably lies in the nature of the nappies themselves. For example, composting wet nappies would reduce the solid waste associated with disposable nappies, although the plastic and non-biodegradable components currently remain an issue. Alternative materials such as hemp and bamboo should be investigated. Use of unbleached or recycled pulp may also provide a way to reduce the environmental impact of disposable nappies.

Reducing the impact of commercially-washed reusable nappies relies largely on reducing cotton consumption. This could be achieved through using the thinnest nappies available. Alternatively, thick nappies could be use, and sold for home-washing applications when they became stained or discoloured. This would provide a credit for reducing cotton consumption, through increasing the lifespan of the nappies. As for home-washed reusables, elasticated or shaped nappies may possibly reduce cotton requirements. Materials other than cotton should also be investigated for reusable nappies. Commercial laundries should also work to reduce energy and water consumption where possible, for example using solar water heating.

Even the relatively low forestry runoff reduction (75 mm per annum) assumed in this study has a major impact on water resource depletion over the life cycle of disposable nappies. This should be considered in future life cycle studies of softwood products. However guidelines are needed to determine how to best to account for water resource depletion associated with forestry, given the large uncertainty in the values, and the strong local effect of rainfall and other variables.

The two disposable nappy faeces disposal scenarios (“flushing” and “direct disposal”) could not be distinguished using the four indicators considered here. Airborne and waterborne emissions, as well as public health effects, need to be accounted for to assess and compare the two disposal options.

This study demonstrates the value of including the range of practices, when comparing systems subject to large variability. Had we selected conditions equivalent to the high impact case for reusable nappies, and the low impact case for disposable nappies, we would not have been able to identify the system with the potential for the lowest environmental impact. While sensitivity analysis will demonstrate which variables have a large effect on results, comparing the range of impacts has allowed us to determine where the difference in nappy systems exceeds the variability within each system.

6. ACKNOWLEDGEMENTS

We greatly appreciate the data supplied by Dick Nobbs and Harley Wright (Kimberly-Clark Australia), Ben Van Balen (Brisbane Nappy Service) and Bruce Pyke (Cotton Research and Development Corporation). Joe Lane reviewed this manuscript, and Marguerite Renouf, Peter Erskine and Bill Clarke provided helpful discussions. This work was supported by a UQ New Staff grant, and a UQ Return to Research grant (EPSA faculty) to K.O'Brien, and a UQ School of Engineering vacation scholarship for Y.-C. Hsu.

7. REFERENCES

1 Choice Magazine *High and dry: our readers and their babies give us the verdict on which nappies rate the best* Choice (Chippendale, Australia) April 33(3), 2007

2 Sauer, B.J., Hilderbrandt, C.C., Franklin, W.E. and Hunt, R.G. *Resource and Environmental Profile Analysis of Children's Diaper Systems*, Environmental Toxicology and Chemistry, vol 13, no 6, pp 1003 – 1009, 1994

3 Vizcarra, A.T., Lo, K.V. & Liao P.H., *A Life Cycle Inventory of Baby Diapers Subject to Canadian Conditions*, Environmental Toxicology and Chemistry, vol 13, no 10, pp 1707 – 1716, 1994

4 Aumônier, S. & Collins, M., *Life cycle assessment of disposable and reusable nappies in the UK*, Environment Agency, Almondsbury, Bristol, UK, 2005

5 Aumônier, S., Collins, M. and Garrett, P. *An updated lifecycle assessment study for disposable and reusable nappies*, Science report SC010018/SR2 Environment Agency, Almondsbury, Bristol, UK, 2008

6 Vertessy, R. *Impacts of plantation forestry on catchment runoff*, Proceedings of National Workshop, July 2000 Water and Salinity Issues in Agroforestry No. 7 Rural Industries Research and Development Corporation Publication No. 01/20, 2001

7 Keenan, R.J., Parsons, M., Gerrand, A., O'Loughlin, E., Beavis, S., Gunawardana, D., Gavran, M. and Bugg, A. *Plantations and water use: a review prepared for the Forest and Wood Products Research and Development Corporation.* Bureau of Rural Sciences, Canberra. 2004.

8 Greenwood, A.J. and Cressell, D.J. *The impact of plantation forestry on runoff in the Mount Lofty ranges, case study: Burnt Out Creek.* Technical Note 2007/11. Department of Water, Land and Biodiversity Conservation, 2007

9 Zhang, L., Vertessy, R., Walker, G., Gilfedder, M. & Hairsine, P. *Afforestation in a catchment context: understanding the impacts on water yield and salinity*, Industry Report 01/07 CSIRO Land and Water, 2007.

10 Lentner, C*., Geigy scientific Tables,* Ciba-Geigy, Basle, 1981

11 Olive, R., *A Life Cycle Analysis of Disposable, Reusable and Compostable nappies under Brisbane conditions***,** BE (chemical) undergraduate thesis, University of Queensland, Brisbane, Autralia, 2004

12 Patterson, R.A., *Salinity – much more than a rural issue!*, 2007 Urban Salt Conference for the Western Sydney Regional Organisation of Councils, NSW Department of Natural Resources, Natural Heritage Trust and Catchment Management Authority, Sydney, 2007

13 Lambert, D., Rainbow Power Company, Personal communication, 31 October 2008.

14 National Greenhouse Gas Inventory Committee (NGGIC), *Australian Methodology for the Estimation of Greenhouse Gas Emissions and Sinks: Workbook for Waste*, Revision 1, Department of the Environment, Sport and Territories, Canberra, 1996

15 Australian Greenhouse Office (AGO), *Greenhouse Gas Inventory 2000*, Australian Greenhouse Office, Canberra, 2002

16 Clarke, W., *Solid and Hazardous Wastes*, in Cromar, N., Cameron, S. and Fallowfield, H. (eds), Environmental Health in Australia and New Zealand, Oxford University Press, Melbourne, 2004

17 Kenway, S.J., Priestly, A.J. and McMahon, J. *Water, wastewater, energy and greenhouse gas emissions in Australia's major urban systems,* Reuse 07, 3rd AWA Water Reuse and Recycling Conference University of NSW, 2007

18 Australian Greenhouse Office, *Analysis of Recent Trends and Greenhouse Indicators 1990 to 2005*, Commonwealth of Australia, 2007

19 Australian Government Department of Climate Change, *National Greenhouse Accounts (NGA) Factors*, January 2008

20 Clark, I., SITA Environmental Solutions, Personal communication, 5 April, 2004

21 Clark I., SITA Environmental Solutions, Personal communication, 30 April, 2004

22 Hannaford, R., SITA Environmental Solutions, Personal communication, January 13, 2006

23 Wright, H. Kimberly Clark Australia, Personal communication, 27 April, 2004

24 Nobbs, D. Kimberly-Clark Australia, Tantanoola Mill, Personal communication, 6 April, 2004

25 Eco Resource Development (ERD), *Economic aspects of growing softwood plantations on farms in the New England region*, New England North West Forestry Investment Group leaflet, 2002

26 Foran, B., Lenzen, M. and Dey, C. *Balancing Act - A Triple Bottom Line Analysis of the Australian Economy,* CSIRO Sustainable Ecosystems and University of Sydney, Canberra and Sydney, 2005

27 Wright, H., Kimberly Clark Australia, Personal communication, 20 January, 2006

28 Queensland Transport, *Performance Guidelines for 14.6 metre long and 4.6 metre high semitrailers in Queensland*, Queensland Transport, 1998

29 Tennakoon, S.B. and Milroy, S.P., *Crop Water Use and Water Use Efficiency on Irrigated Cotton Farms in Australia*, Agricultural Water Management, vol. 61, pp. 179-194, 2003

30 Kalliala, E.M. & Nousiainen, P. *Life Cycle Assessment Environmental Profile of Cotton and Polyester-Cotton Fabrics*, Autex Research Journal, vol. 1, no. 1, pp. 8-20, 1999

31 Pyke, B., Cotton Research and Development Corporation, Personal communication, 12 December, 2005

32 Van Balen, B., Brisbane Nappy Service, Personal communication, 15 April, 2004b

33 Van Balen, B., Brisbane Nappy Service, Personal communication, 12 March, 2004a

34 Van Balen, B., Brisbane Nappy Service, Personal communication, January 18, 2006

35 Light, K.L, Chirmuley, D.G. and Ham, R.K. *A laboratory study of the compaction characteristics of disposable diapers in a landfill*, Resources, Conservation and Recycling, vol. 13, no. 2, pp. 89-96, 1995

ALCAS

AUSTRALIAN LIFE CYCLE ASSESSMENT SOCIETY

PRESENTER BIOGRAPHICAL INFORMATION

Kate O'Brien in a Lecturer in Environmental Engineering at the University of Queensland, Brisbane. She received her BE (Chem Hons) and BSc from the University of Queensland, and her PhD from the University of Western Australia. Her research interests include environmental modelling, life cycle assessment and hydrobiological modelling.

Rachel Olive is a Transaction Adviser with the Peron Group in Brisbane. She is currently working on various transactions including Hale Street Link Tolling Revenue Collection Service Project and the Townsville City Council Water Upgrade Project. She has a BE (Chem Hons) and LLB (Hons) from the University of Queensland.

Yu-Chieh Hsu received her BE (Hons) in 2007 from the University of Queensland with a chemical and biological engineering double major. She is currently a PhD candidate at the University of Queensland, investigating polyethylene greenhouse films for increased crop production.

Luke Morris, Richard Bell and **Nick Kendall** are completing their BE (Chem) at the University of Nottingham. They participated in this project while on student exchange to the University of Queensland in 2008.