CRC FRESHWATER ECOLOGY TECHNICAL REPORT

The Effect on Sewage Phosphorus Loads of Using Phosphorus Free Laundry Detergent

Thurgoona Case Study

G Ransom, P Morgan and P Cullen
CRC for Freshwater Ecology
University of Canberra
ACT, 2601

and

D Allen, D Sinclair and D McGregor
Albury City Council
PO Box 323, Albury, NSW, 2640

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Executive summary

In 1997, Albury City Council and the Cooperative Research Centre for Freshwater Ecology, with funding from The New South Wales Department of Land and Water Conservation, conducted a study into the contribution of laundry detergents to sewage phosphorus loads.

The study, conducted in three stages over six months, measured both the flow and phosphorus concentration of sewage from a catchment of around 350 households at Thurgoona near Albury, NSW. Baseline data was collected during the first phase of the study. The second phase of the study, the main study, measured the impact of phosphorus-free detergent usage while the third phase assessed long term changes in the community's use of phosphorus-free detergents.

The study resulted in a an upper limit of 47% and a lower limit of 24% reduction in phosphorus in raw sewage when 64% of the community used phosphorus-free laundry detergent. This translates to a reduction of the existing load of 120 kg/day to around 65 to 90 kg/day for the total Albury community.

Reductions of this level would have a significant impact on phosphorus control at wastewater treatment plants. Potential savings of tens of thousands of dollars per year arising from a decrease in treatment costs could be expected, and the risk of increasing salinity and other pollutants resulting from the chemical removal of phosphorus would be significantly reduced.

The role of phosphorus

Phosphorus is an important constituent of all life. This nutrient occurs naturally in most plants and animals and readily enters the food supply of humans from these sources. Phosphorus also occurs naturally in most soils. Australian soils are generally poor in phosphorus, so it is added by way of fertilisers such as superphosphate. Thus most of our inland waters to contain some levels of phosphorus, either from natural sources or from those derived from human activity.

Excessive amounts of phosphorus may lead to the increased growth of algae and other micoorganisms, causing water quality to degrade. Water containing large amounts of algae can become unsafe to drink. Ingestion of blue-green algae toxins can cause vomiting and diarrhoea, and may have longer term effects such as liver damage and the promotion of tumour growth. Contact with algal blooms can cause skin irritation, thus impacting on the recreational use of water.

Several conditions are necessary for excessive algal growth:

- The concentration of phosphorus reaches a critical level.
- The normally more inert forms of phosphorus found in soils are augmented by more biologically active forms found in sewage effluent, including those from human waste and laundry detergents.
- Parameters such as flow, turbidity, temperature and sunlight are at suitable levels for algal growth.

Good management of phosphorus requires that natural levels are not significantly exceeded. Naturally occurring phosphorus can be augmented from many sources. Non-point, or diffuse, sources include the run-off of agricultural phosphorous-based fertilisers.

Point sources such as sewage treatment plants are another source of non-naturally occurring phosphorus. Control of phosphorus levels using chemical removal processes is undertaken at sewage treatment works, to ensure that the amount discharged to the environment is within acceptable limits. It is important however to also initiate control at the origin, by stopping phosphorus from entering wastewater. A reduction in the amount of phosphorus reaching the treatment plant translates to lower running costs for the plant, while reducing the risk of increasing salinity and other pollutants resulting from the chemical removal of phosphorus. Source reduction also ensures that less phosphorus reaches the environment during periods of system overload or failure when untreated water is released. Much of the phosphorus in wastewater originates from human excreta and detergents which are discharged after usage into the sewerage system. Thus it is important to understand what urban activities contribute to phosphorus levels in wastewater, and their relative magnitudes.

Background to the Thurgoona study

The Albury City Council has long been at the forefront of authorities seeking to better manage their urban water resources. The PhosWatch campaign saw the phosphorus in influent sewage reduced from 142 kg/day to 112 kg/day as a result of an extensive education campaign aimed at changing the community's laundry and washing habits. A significant part of the PhosWatch campaign was the thrust to low and non-phosphorus laundry products.

The aims of the Albury-Wodonga-Corowa Phosphorus Action Campaign (PhosWatch) included:

1. To increase public awareness about the contribution phosphorus makes to increasing nutrient levels in our inland waters.
2. To provide the public with information about the sources of phosphorus in an urban context.
3. To provide information on what actions individuals can take to help minimise phosphorus in particular, and pollutants in general, at the source.

4. To quantify phosphorus reduction in sewage as a result of encouraging, at a local level, the use of zero/reduced phosphate detergents.
5. To provide valuable research data as part of the on-going program to improve water quality and to reduce the incidence of algal blooms in inland streams.
6. To act as a pilot for expansion of the program throughout NSW and nationally.
7. To provide input to the State Algal Management Strategy and to the Agriculture and Resource Management Council of Australia and New Zealand.

The Thurgoona Case Study follows a recognition that a follow-up campaign to the successful PhosWatch campaign was necessary. More information was needed on the contribution that laundry detergent makes to the phosphorus load, and what level and goals could be set if a campaign to use more non-phosphorus laundry products were to be initiated.

The Thurgoona Case Study

A sub-section of the Corry's Wood and St Hilaire estates of Thurgoona were chosen to participate in the study. The raw sewage flow and phosphorus concentration from the 356 occupied homes in the catchment were monitored during the three phases over six months in 1997.

The first phase, conducted during school term in March, was aimed at determining the community's normal usage pattern. The baseline data gathered during this period were acquired without any community announcement that a new project to study phosphorus had been initiated.

The second period, the main study period, measured the effect of using phosphorus-free laundry detergent on sewage phosphorus load. It commenced shortly after Easter with the announcement of the planned trial in the estates of St Hilaire and Corry's Wood. The announcement was followed by letter deliveries to households in the catchment, and with community meetings. A social survey, also conducted at this time, revealed that of the 385 houses in the study area, 356 were occupied. Of the occupied houses, 229 agreed to participate in the study and were given a free, eight week supply of non-phosphorus laundry detergent from a range of three products purchased by the Albury City Council. This allowed for a main sampling period of seven weeks running from April 22 through to June 10. The length of this period allows significant statistical averaging as well as providing an insight into the daily variations that exist within the normal weekly cycle. Like the baseline study, this study period did not include school holidays, although it ended with a public holiday, the Queen's Birthday. The average temperature during this main study declined by more than 10 degrees as the community moved from a warm autumn to early winter. A social survey, undertaken after the main study period ceased, gathered data on the effectiveness of the offered laundry detergent and other aspects of the trial.

The third and final period, the follow-up study, ran from August 2 to August 26, another period of continuous schooling. This part of the study was aimed at gauging the medium term success of modifying the community's laundry detergent usage habits. It was conducted some time after the last distribution of free, non-phosphorus laundry detergent, to ensure that any remaining supplies had been used. Chemical samples were collected for 21 days, however the flow record was interrupted by a recorder failure at day eight and difficulties in stabilising the record until day 12. Thus only limited data is available from this period.

Results

The results from the Thurgoona study are very promising, especially when viewed with the available social data. The overall reduction in phosphorus load during the period of phosphorus-free laundry detergent usage was 47%. This figure represents an upper limit on the amount of reduction, and is due to both changes in flow and changes in phosphorus concentration from the baseline to the main study period. The measured flow data for this study are inconclusive, which translates to uncertainties in the measured load to give a possible lower limit of reduction of 24%. This represents a load change due only to change in phosphorus concentration, and is therefore independent of changes in flow.

These results were obtained with a community participation rate of 64%, 25% of whom were already using phosphorus-free detergent. No attempt is made to adjust this result for the participation factor as there will always be members of the community who will prefer to use phosphorus detergents. For the study community, the reduction was from a baseline load of 2.5 kg/day to 1.3 kg/day. Assuming similar participation levels and a dominantly domestic source, it is anticipated that, on a city wide basis, the average daily load of phosphorus discharged to the treatment works could fall from the current level of 120 kg/day to around 65 kg/day, although in reality this latter figure would be elevated by some industry contribution.

The results also indicate that despite the availability of free laundry detergent and an increase of laundry activity due to its availability, the community also practiced water conservation which is part of the overall strategy. Indeed an in-depth study of flow into the Albury treatment works determined that over the last eight years, despite increases in population and industry, that there has been no net increase in flow. The practice of using full laundry loads is believed to be a significant contributor to this flow reduction, along with other *waterwise* practices.

A more detailed analysis of the reduction in phosphorus load shows that the decline is greater for the flow component, assuming a constant concentration, than it is for the load component assuming constant flow. Two major possible causes are:

1. Laundry activity is associated with a period of rapidly changing flow. The flow changes over a factor of 10 during the principal laundry period.
2. Errors in the individual depth readings, which are converted to flow, are proportionally greater than those in the phosphorus concentration determination.

The analysis of individual components and their interaction is able to place upper and lower limits on the results of the study. The lower limit for the reduction in phosphorus load is that component estimated to be due entirely due to changes in concentration. This was determined to be a 24% change. While not as significant as the overall value of 47% it still represents a significant change. If this level is applicable then the effect on the inflow into the treatment works would be to lower the current level of 120 kg/day to 90 kg/day.

Analysis of the follow-up study data shows a partial return to baseline community washing habits. Phosphorus load differs by only three percent between these two periods, however analysis shows that the proportion of components has changed. Flow increased by 15% from baseline levels while phosphorus concentration decreased by 10% (0.26 kg/day). The decrease in phosphorus concentration occurs mainly during the mid morning, the time of most laundry washing, indicating some acceptance and continued use of phosphorus-free laundry detergent following the main study period.

The future

This study highlights the contribution that laundry detergent phosphorus makes to the total load of phosphorus entering a sewage treatment plant. Environmental Protection Agency standards for the release of water from plants such as Albury require that the level of phosphorus be less than 0.3 milligram/litre on a 90 percentile basis. Other studies, notably the study undertaken by Melbourne Water at Whittlesea, suggest that biological nutrient plants, such as that operated by Albury City Council, operate more efficiently at lower level of influent phosphorus and thus may be able to reach Environment Protection Authority standards without the assistance of the current practice of chemical dosing.

Reductions or even elimination of chemical dosing may remove potential salinisation and mineral pollution problems as well as creating savings by reducing dosing agent costs. This evidence points to a need to review the operations of biological nutrient removal plants and the practice of chemically dosing the effluent.

It is therefore recommended that, should funding become available, a detailed study of the Albury City Council's wastewater treatment plant be carried out to determine:

1. The current levels of the influent phosphorus load and its variation.
2. The average residence time for particles participating in the biological process.
3. The tuning of the biological process for the optimal removal of phosphorus and other nutrients such as nitrogen.
4. The current levels of phosphorus and nitrogen before chemical dosing.
5. The current levels of phosphorus, nitrogen and unused dosing agent in the overall effluent.

Depending on the nature of the above results it is proposed to then seek community cooperation for a major trial, to determine the optimal characteristics of the plant under a reduced phosphorus load by repeating a significant portion of the above monitoring.

It is stressed that there are significant savings as well as significant environmental gains to be made if the current pointers to improved efficiency under reduced phosphorus load can be validated. The ability to cause and sustain these expected efficiencies is strongly linked with the level of phosphorus in laundry detergent and the ability to influence and change the laundry detergent preferences and habits of the community.

Chapter 1

Introduction

Phosphorus plays a dominant role in the eutrophication of waterways as it is one of the essential ingredients required for the production of cellular matter.

The connection between the supply of phosphorus and the level of algal biomass was enunciated in the OECD/Vollenweider model (Vollenweider and Kerekes 1982), and subsequently reinforced by Sas (1989). The applicability of these non-Australian studies to the more turbid Australian conditions has long been debated. Harris (1994) has shown that the larger algal cells or colonies, such as those of the blue-green cyanobacteria algae, favour high phosphorus concentrations, and reducing these concentrations shifts the predominant species away from these cyanobacteria types.

The connection between the supply of phosphorus and algal mass is further complicated by the level of bioavailability of the phosphorus. Dissolved reactive phosphorus, usually in the form of orthophosphates, is generally considered necessary for algal growth. It is also generally agreed that the particulate forms, usually measured in a total phosphorus determination, are less available for plant growth. Unfortunately no models currently exist that describe the conversion process between the two forms or the mechanism under which algal species are able to use particulate phosphorus which can be remobilised if not permanently bound.

The supply of phosphorus to waterways is broken into point and non-point sources. The latter sources include the application of fertilisers to agricultural land and the uptake or dissolving of naturally occurring phosphorus. The former, the topic of this paper, are primarily due to urban and industrial activity with urban activity generally being considered the major component.

This major point source is the subject of considerable debate. In most sewage treatment plants it is normal for phosphorus to be removed both by a biological nutrient removal process and by dosing the effluent with mineral salts such as alum, ferrous chloride or ferric chloride to precipitate the phosphorus. This incurs chemical costs as well as the potential of increasing the background levels of the dosing agents themselves as the tendency is to overdose. A significant drawback to relying on this approach is the release of untreated water and hence phosphorus to the environment. This can occur either through exfiltration when water leaves the system through leaking joints, cracks and breaks in the pipe, or through overflow when the system is overloaded as is often experienced in times of abnormally heavy rain, or when pipes become blocked. Since the strategy for phosphorus management in a catchment should include control of phosphorus at the source, it is important to understand which urban activities contribute to phosphorus levels in wastewater.

The majority of phosphorus in wastewater comes from human excreta and from laundry detergents, with the detergent component being the most amenable to reduction and control. Phosphorus is commonly added to detergent to enhance the removal of dirt from clothing. It removes calcium from the water hence softening it and preventing the redeposition of dirt. Alternatives do exist however, and most phosphorus-free detergents contain zeolites and/or polycarboxylic acid to carry out the function of softening the water (Cullen, Heretakis & Herington 1995).

This report describes a recent study at Thurgoona, near Albury that was aimed at understanding the laundry detergent component of phosphorus in sewage.

Chapter 2

The Thurgoona Laundry Detergent Phosphorus Study

2.1 Background

The Thurgoona Laundry Detergent Phosphorus Study was conceived as a follow-up to a study conducted by Melbourne Water at Whittlesea (Cullen, Heretakis & Herington 1995). The Whittlesea study was the first in Australia to attempt to quantify the contribution that laundry detergents make to influent phosphorus load and the effect that this load has on the efficient operation of a biological nutrient removal plant.

The project was located at Whittlesea, a small township north of Melbourne containing just over 400 dwellings. The town also contained a school and a small shopping area which included a laundromat. Most of the residents were employed in the northern suburbs of Melbourne. A small percentage of households were engaged in shift work.

The Whittlesea study ran over three months with three phases. The first was a 10 day period when baseline sampling was undertaken before the community was told that a phosphorus trial was to be conducted in their town. The second phase was a six-week period during which free phosphorus-free laundry detergent was available at the local supermarket. The laundromat was also stocked with free phosphorus-free laundry detergent. Sampling was resumed two weeks after the phosphorus-free detergent was made available to ensure maximum uptake of the detergent. Social sampling indicated that 79% of the community participated. Finally, sampling was conducted after free distribution ceased to estimate the effect that the campaign had on local habits.

In the Whittlesea study both the influent and effluent streams of the sewage treatment plant were sampled for total phosphorus at hourly intervals. The inflow volume was recorded by pump switching times and rates while the outflow was measured using a vee-notch weir. This arrangement led to many problems in fully and adequately describing the flow and hence the influent phosphorus load. These were generally overcome by correlating the influent and effluent streams and then using this correlation to deduce the influent flow.

Results from the Whittlesea study showed that phosphorus loads were significantly reduced, by some 25%, when the phosphorus-free detergent was in general use. There were periods, especially in the high flow, high load morning period when most of the normal laundry activity took place, where reductions were higher, indicating that laundry detergents were a significant component of the influent phosphorus load. In addition to this load reduction, the trials delineated the now well established twin peak structure of daily load with the dominant morning peak at about 10.00 a.m. while a lower and broader evening peak occurs near 7.00 p.m. The remaining significant result was the more efficient biological removal of phosphorus by the plant when peak phosphorus levels were reduced.

A follow-up study to Whittlesea was needed to both validate the important results and to place tighter constraints on the level of reduction by better controlling the basic observational data.

The Albury-Wodonga inland growth centre is a community of about 100,000 people situated in the upper catchment of the River Murray. As such it draws its domestic water supply from the river as a first-use community. Previously, most of the water was returned to the river for reuse by other communities further down stream. The Albury-Wodonga community is keen to ensure that its use of the river has minimal impact on downstream users and has had a long term commitment to a phosphorus reduction strategy through its PhosWatch campaign. The PhosWatch campaign was able to reduce community phosphorus loads from 142 kg/day to levels near 112 kg/day. The involvement of a phosphorus aware community was considered essential to the success of a replication study as the social survey and the results from Whittlesea showed that without a commitment by the community to such a program the gains are short lived. Additionally, since the community must be made aware of the aims of the project, community education is necessary to ensure high levels of participation. Albury-Wodonga, with high levels of community awareness, was thought to be more receptive than many other communities for a new phosphorus trial. Thus the Albury City Council, the CRC for Freshwater Ecology and the New South Wales Department of Land and Water Conservation agreed to undertake a new study which had the following major aims:

1. To quantify the proportion of phosphorus in influent sewage that comes from laundry detergents (via laundry wastewater).
2. To monitor the effect of a phosphorus awareness campaign on the community's laundry habits.

Portions of the estates of Corry's Wood and St Hilaire in Thurgoona, see Figures A.1 and A.2, were used as the target of this study. The reasons for choosing this region were:

- The residents of Thurgoona are generally middle income earners. The socio-economic mix of households is uniform as the estates were built over a relatively short period. This would help ensure a high participation rate in the study.
- The sewerage system is new and hence not subject to stormwater inflow or infiltration which would compromise the study.
- There is no industry in the estates, so results show the effect on a purely domestic community without having to be adjusted for phosphorus generated from other sources.

- Good plans of the sewer system with known grades were available. This meant that flow, a significant problem in the Whittlesea trials, could be calculated more accurately and hence errors due to flow could be minimised.
- Reasonable and safe access to the sewer system for the installation of flow measuring and chemical sampling devices was guaranteed due to the existence of wide easements.
- The number of occupied households in the estate connected to the sewer was known to be 356. A number similar to the Whittlesea experiment (400 households) provided a better comparison with the Whittlesea results while maintaining a statistically significant sample size.

2.2 The Thurgoona Case Study

The Albury City Council's investigation became known as the Thurgoona Case Study. It used the same layout as the Whittlesea experiment, with a major planning phase which was followed by three study periods. The first period was the baseline study in which the influent was monitored for flow and chemistry without advising the target community that such monitoring was in progress. This period was used to establish a pattern of normal community activity.

The second period was the main study. This commenced with a campaign to make the community aware of the study and to seek their support. Once the phosphorus-free detergent was distributed, wastewater monitoring commenced. Monitoring continued for the next seven weeks, during which time the supply of phosphorus-free detergents to households was continued.

Finally a follow up study was conducted. This period, nearly eight weeks after the the supply of free detergent ceased, was used to measure the longer term effect of the campaign on the community's washing habits.

Because these three periods needed to be well separated from each other, the monitoring stages of the Thurgoona case study took six months to complete. Figure 2.1 shows the three periods of the Thurgoona study as well as those periods where community consultation occurred. Also included are the dates of school terms and public holidays to determine the relative similarity of conditions within the study periods.

2.2.1 Planning

The major tasks undertaken in this part of the study were:

Access to sewer trunk

A pre-existing access point was located on the trunk sewer servicing the Thurgoona estates of Corry's Wood and St Hilaire. This access is on a bend in the line (Figure A.2) and so was suitable for chemistry sampling but not for flow, so another access point needed to be constructed. Major technical needs for this second access point, all related to ensuring the applicability of the Manning's flow formula, were:

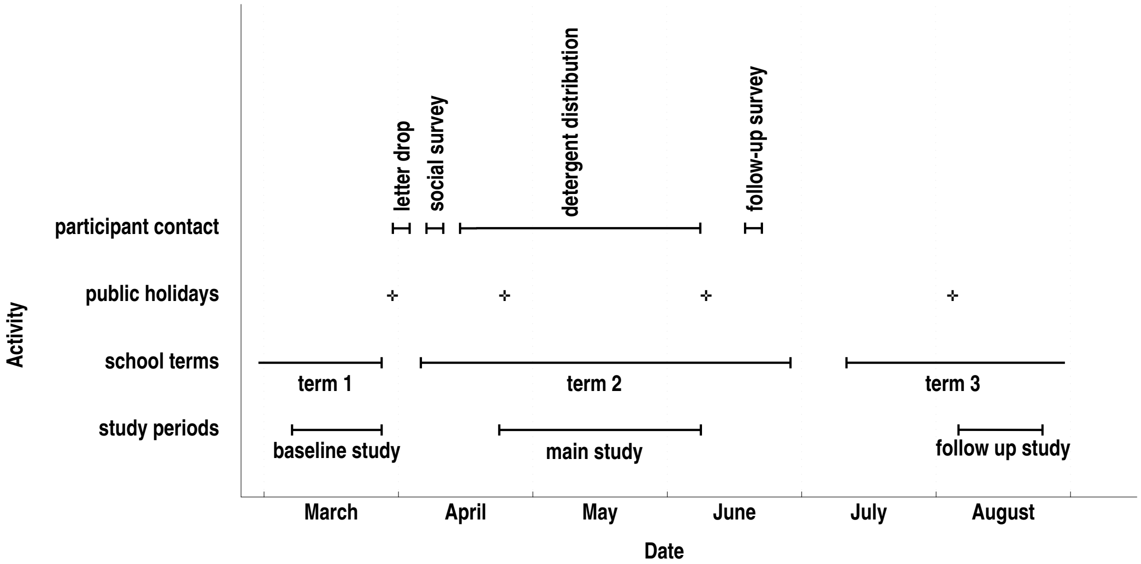

Figure 2.1: Time line of the Thurgoona Case Study

- That the sewer grade was uniform for a considerable distance upslope from the sampling point thereby ensuring that the flow was uniform and lamina.

- That the trunk sewer was relatively new and hence could be expected to be relatively smooth in cross-section. This newness could also be expected to minimise infiltration and inflow effects during rain as well as avoiding partial blockages of the sewer.

- That the cross-section of the trunk sewer was sufficient to ensure that all flow regimes could be correctly modelled. In hindsight it is recognised that a smaller cross-section pipe would have been more appropriate for the study conditions experienced. However it is doubtful if this condition could be adjusted while ensuring that the first two needs were met.

The new access point fitting the above requirements was located 25 m upstream of the chemistry sampler, see Figure A.2.

Flow

Experience at Whittlesea indicated that good flow data is critical to any study, as variations in flow are significant. Albury City Council has several ultrasonic depth measuring instruments which were used for sewer infiltration and maintenance studies. They are portable and readily installed. Since these instruments offer a non-intrusive method of measuring flow they were adopted for the study. Section 3.1 covers the operation of these flow recording devices.

Sampling and chemical analysis

A major cost in phosphorus studies has been that of chemical analysis. While costs vary between the major laboratories, a mean bulk rate value of about \$10 per sample is an appropriate planning cost. Since this study would comprise three extended monitoring periods there was a need to minimise these costs. This was achieved by using an in-house bulking method, detailed in Section 3.2. The adopted bulking strategy reduced the standard number of samples by half.

Despite this reduction in sampling, planning indicated that the number of samples generated over 28 days would exceed the capacity of both the Albury City Council's and the CRC for Freshwater Ecology's laboratories. A method which saw alternate days of the samples analysed at The Albury City Council's and CRC's laboratories was adopted, with a set of comparison samples analysed to ensure that no bias entered the data.

Trial

An installation and procedures trial was undertaken in December 1995. The major operational need identified in this trial was the need for constant cleaning of the chemistry sample intake head to ensure that it remained unblocked, especially during low flow. The head of the sampler, about 2 cm in diameter, lies longitudinally in the sewer pipe. Inspection found that it neither impeded nor pounded the flow.

2.2.2 Baseline study

The baseline study commenced on March 6 and ran for 21 days.

Temperatures during the study period were typical of early autumn in the region. Water usage patterns in Albury, as indicated by the total flow into the Albury treatment plant, were stable and representative. There are no indications that this baseline period was anything but a representative snapshot of the Corry's Wood and St Hilaire communities at the time.

2.2.3 Main study

The main study began with a letter drop to residents in Corry's Wood and St Hilaire explaining the purpose of the study and requesting their participation (Appendix D). This was followed by a telephone survey, the pre-study questionnaire (Appendix E). Finally, phosphorus-free detergent was distributed with residents choosing one of three offered brands. Initial planning called for a two-week waiting period between the request to use the phosphorus-free laundry detergents and the start of sampling to ensure that the sewer system was in equilibrium with the new regime. This holding period was dropped in favour of continuous monitoring from the request to use date, so that both system equilibrium times and community response could be more effectively monitored. Thus the sampling period was increased from three to five weeks. As it turned out the supply of phosphorus-free laundry detergent was sufficient for the participants to continue to use the free, no phosphorus product for another two weeks, thus providing a seven week data set.

2.2.4 Follow-up study

The final part of the study was the follow-up period. Shortly after the end of the main study period another telephone survey, the post-study questionnaire (Appendix F), was conducted to gauge the community's acceptance of phosphorus-free laundry detergents and the perceived ability of phosphorus-free products to perform laundry washing to at least the same level as the conventional phosphorus products.

The monitoring period, which began on August 1 and ran for 29 days, was aimed at determining the long and medium term changes to the community's laundry habits. This component ran about eight weeks after the free distribution stock was exhausted. It was planned to ensure that households had used their supplies of free issue detergent and needed to replenish their own laundry detergent.

Chapter 3

Description of the data

This section describes in both quantitative and qualitative terms the data available for this study, and details the data pre-processing strategy and options.

The two major components of the available data are flow and phosphorus concentration. The two are quite different. The latter is a laboratory parameter that is usually measured with precision. It is a point sample that must be interpolated to apply over a significant period. The former, the flow, is a relatively imprecise time series from a frequent observation process.

The data collected is given in Table 3.1.

Table 3.1: Period of flow and chemistry data

Study period	Data	Start		Finish		Purpose
		Time	Date	Time	Date	
Baseline study	Flow Phosphorus	1155 0920	06-03-97 07-03-97	1745 0840	07-04-97 28-03-97	Collect baseline data
Main study	Flow Phosphorus	1530 0920	23-04-97 22-04-97	1410 0840	11-06-97 10-06-97	Monitor effect of NP detergent substitution
Follow-up study	Flow Phosphorus	1635 0920	01-08-97 05-08-97	0930 0840	29-08-97 26-08-97	Monitor change in detergent usage habits

Since there was a need to time align the flow and concentration records, processing of each data set began on the first whole day boundary, 0000, and ended on the last 24 hr boundary, 2355. These processing boundaries for the data are shown in Table 3.2.

3.1 Flow

The fundamental relationship used in an ultrasonic depth logger is

$$d = v \cdot t \tag{3.1}$$

Table 3.2: Days processed in each study period

Study period	Start		Finish		Number of days
	Time	Date	Time	Date	
Baseline study	0000	08-03-97	2355	27-03-97	20
Main study	0000	24-04-97	2355	09-06-97	47
Follow-up study	0000	06-08-97	2355	25-08-97	20

where d is the distance travelled by the ultrasonic pulse with velocity v, in time t.

The velocity of sound in dry air is not a constant but varies with temperature. The relationship is

$$v = \sqrt{\frac{\gamma RT}{M_{air}}} \tag{3.2}$$

where

R is the universal gas constant, 8.31 $\text{J/mol} \cdot \text{K}$
M_{air} is the molecular weight of dry air, 0.02893 kg/mol
γ is the ratio of molar heat capacities, 1.4
T is the temperature in degrees Kelvin (K).

For standard conditions of 25° (298.16°K) the velocity of sound is 346.29 m/s.

3.1.1 The ultrasonic flow meter

The portable ultrasonic meter produced by *Microcom* was used to measure the depth of influent in the channel for the Thurgoona study. The basic setup for calibration is shown in Figure 3.1 and the logger and sewer access point are shown in Figure 3.2.

The sensor and logger are initially positioned as pictured over a striker plate whose reflection surface is set 150 mm above the bottom of a metal rod. This striker plate removes variations in flow during the calibration phase. The user enters the depth of flow, d_0, as 150 mm, and the maximum range (the maximum depth that can be measured, in this case the radius of the pipe, 225 mm). The logger then prompts the user to move the sensor vertically until its height above the bottom of the channel $(d + D)$ is equal to the maximum range, 225 mm, plus the deadzone of 760 mm making a total of 985 mm. The deadzone is the minimum height that the sensor must be above the surface in order that the outgoing pulse does not interfere with the returning signal. This adjustment ensures that the height of the flow will never overlap the deadzone. After calibration, the striker plate is removed, and the logger starts recording data measured to the surface of the flow.

The relationship between measured and given quantities for the first reading r_0, using equation 3.1, is

$$r_0 : \quad t_0 \cdot v = D_0 \quad \rightarrow \quad d_0$$

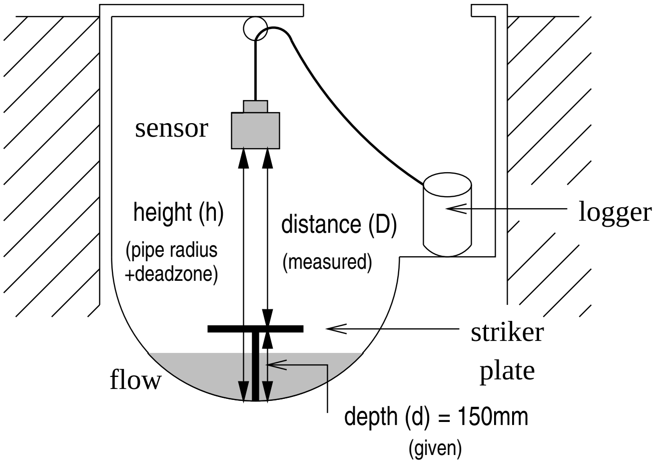

Figure 3.1: Calibration of ultrasonic flow meter

Figure 3.2: Flow logger and sewer access point

where t_0 is the measured time of flight of the ultrasonic pulse (s)
v is the adopted speed of sound, 348.8 m/s
D_0 is the calculated distance of the sensor above the striker plate (m)
d_0 is the known depth of flow given during calibration, 150 mm.

The speed of sound at the manufacturers calibration temperature of 25°C is 346.29 m/s in dry air. The adopted value used was determined empirically by the manufacturer in order to take into account non-linear effects on the meter such as filter ramp-up times.

Subsequent readings, $r_1, r_2, \cdots, r_n$, use the change in distance measured from the first reading r_0 to calculate depth, rather than the actual distance itself. As the initial time of flight to depth relationship is known, a change in the former can be computed as a change in distance and applied to the first depth reading to derive the current depth.

$$\begin{array}{rlcl} r_1: & (t_1 - t_0)\cdot v = \Delta D_1 & \rightarrow & d_1 = d_0 - \Delta D_1 \\ & & \cdots & \\ r_n: & (t_n - t_0)\cdot v = \Delta D_n & \rightarrow & d_n = d_0 - \Delta D_n \end{array} \tag{3.3}$$

3.1.2 Observation uncertainty

As with any measurement equipment, the depth values recorded by the flow logger contain errors. In order to quantify these errors, potential sources were identified and then investigated.

Using Equation 3.3 as the adopted model and substituting Equations 3.1 and 3.2 into the second term we obtain

$$d_n = d_0 - \sqrt{\frac{\gamma RT}{M_{air}}}\,\Delta t. \tag{3.4}$$

From Equation 3.4 the total error, δd_n, is

$$\begin{aligned} \delta d_n &= \delta d_0 - \sqrt{\frac{\gamma RT}{M_{air}}}\,\delta(\Delta t) - \frac{\Delta t}{2}\sqrt{\frac{\gamma R}{M_{air}T}}\,\delta T \\ &= \delta d_0 - v\,\delta(\Delta t) - \frac{1}{2}\frac{(\Delta t)v}{T}\,\delta T \end{aligned} \tag{3.5}$$

The three terms in Equation 3.5 represent error components in the measurement of depth. The first term, δd_0, is the error in determining the initial depth, or the calibration error. The second term, containing $\delta(\Delta t)$, is the error due to errors in timing, commonly referred to as the resolution of the logger. The third term, containing δT is the error due to the effect changes in temperature have on the velocity of the pulse. These errors are detailed in the next three sections.

Temperature effects on depth measurements

It was shown in Equation 3.5 that a component of the total depth measurement error arises from changing temperature. A change in air temperature affects the velocity of the ultrasonic pulse and hence affects the calculation of depth. The variation of calculated depth, as a function of temperature variation over each of the three data sets of Table 3.1 is given in Table 3.3. These calculations use a sensor height of 0.985 m (range + deadzone) and an average depth of 40 mm. Since the changes in distance range are small when the maximum or minimum depths are used, the ranges given for an average depth can be taken to apply for any depth.

The initial and final temperatures given in Table 3.3 are those values that are modelled by performing a linear regression of the observed temperature, and therefore represent seasonal changes in temperature rather than daily fluctuations. The variation in distance range, and hence depth, is significant over each study period clearly indicating that it must be accounted for in a comparative study.

Table 3.3: Result of temperature variation on measurement of a 945 mm distance

Study Period	Initial Temp (°C)	Final Temp (°C)	Distance Range (mm)
Baseline study	24.0	18.2	-8.96
Main study	17.7	12.5	-8.20
Follow-up study	11.0	11.2	0.32

Each data set is calibrated at the first meter readings, with reference to a known depth (Section 3.1.1). This initial mapping is correct regardless of temperature because of the empirical nature of calibration, so it is only subsequent changes relative to the temperature at calibration that will have a perturbing effect on depth measurement. In order to be able to correct for these variations, it is necessary to know the temperature of the sewer at the time of calibration. The flow meter records temperature information at 15 minute intervals, however the initial temperatures recorded in this study do not represent the actual temperature of the sewer. This can be seen in Figure 3.3, where the recorded temperature for the first four days of the baseline study is plotted. Weather data from Albury airport confirms that temperature patterns on these four days were similar, yet the initial temperature recorded by the logger is eight degrees higher than the average temperature recorded at the same time, 12.00 midday, on the subsequent three days.

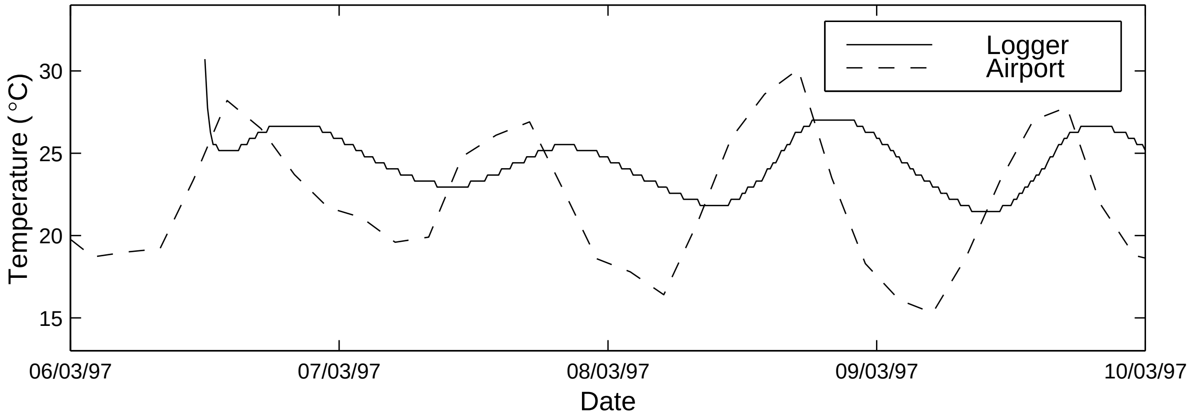

Figure 3.3: Comparison of temperature at Albury airport and temperature recorded by the flow logger for the first four days of the baseline study period.

It was surmised that this high initial temperature was caused by two factors. Firstly, the temperature sensor is within the logger unit, and when the unit is first set up in the sewer the logger is at the temperature of its previous environment, an atmosphere controlled office and for a short time a transport vehicle. It would take time for the logger to adjust to the temperature of the sewer, so these first readings would therefore be representative not of the sewer temperature, but of the location the logger was stored before setup. Secondly, it is possible that in removing the sewer cover to set up the equipment, the temperature in the sewer began to equalise with the surface temperature. During the day the sewer is usually cooler than the outside air, so a resultant increase in sewer temperature could be expected from this effect.

The loggers in each period show a similar two stage process of reaching temperature equilibrium, a rapid reduction phase lasting 45 minutes to almost two hours, followed by a longer six to 14 hour phase of slower, smaller temperature reduction. It was postulated that the first period of rapid temperature reduction was a result of the logger cooling to the sewer environment, with the second period of slow return to average temperatures representing the temperature in the sewer, it having heated by a few degrees while the cover was removed. This would have enabled the true temperature at calibration time to be easily identified, by selecting the point at the end of the rapid reduction phase.

To test the above hypothesis an experiment was performed with two of the flow loggers. The first was placed *in situ* and left for 27 hours to reach temperature equilibrium with the sewer. A second logger was then placed in the sewer, following the usual setup procedure. The first logger records the true sewer temperature, while the second logger shows the effect of operating the meter directly after it has been in storage and transported to the site, without acclimatisation (Figure 3.4). The same two phase process to reach temperature equilibrium can be seen here as in the study data. It is clear that the second slow adjustment phase, ΔT_2, from 2.00 p.m. on April 8 to 4.00 a.m. on the 9th, is not due to any rise in the sewer temperature. If so, the first logger would have also recorded this rise. Instead it appears that the logger is able, within two hours, to lose 60 to 70% of its excess heat. At this point however, heat loss slows greatly and temperature equilibrium is not reached for a further six to 14 hours. If there is any increase in sewer temperature resulting from the setup process it is not apparent from this investigation, and is assumed to be insignificant.

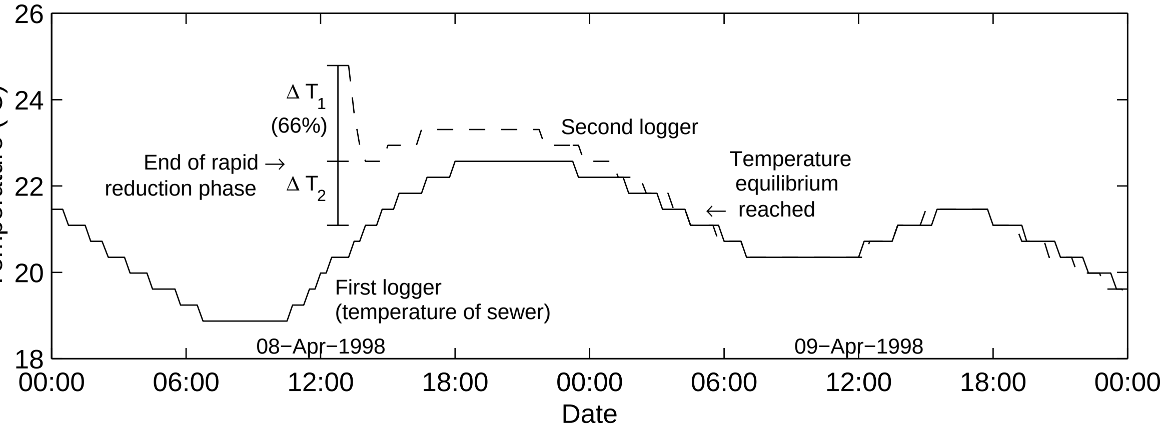

Figure 3.4: The second and third day of an experiment to quantify the rate at which the logger reaches temperature equilibrium with the sewer. At this stage, the first logger has been left *in situ* for 24 hours, and is recording the true temperature in the sewer. A second logger is placed in the channel, and shows a two phase process to reach temperature equilibrium, totalling 14 hours.

While the exact sewer temperature at the time of calibration cannot be identified, a good estimate can be made. This study shows the rapid phase of temperature reduction, ΔT_1, to be 66% of the total reduction to reach equilibrium. The value of this proportion is supported by data from the baseline and main study periods. The initial temperature of the sewer can be estimated by subtracting from the recorded temperature the first reduction (ΔT_1) and the slower reduction (ΔT_2), calculated as 34% of the total reduction $\Delta T_2 = 0.515\Delta T_1$.

Once the calibration temperature of each data set has been estimated, it is possible to correct depth measurements for variation in temperature. Time of flight data is recovered from each depth reading, using an assumed sensor height of 0.985 m above the channel bottom (Equation 3.1). This information can then be used with the temperature dependent theoretical velocity at each data point to recalculate the distance measured and hence obtain the true depth of liquid in the channel.

The effect of temperature correction is shown in Figure 3.5. The cumulative change in depth in the main study has been reduced significantly, from -12 mm, to 4 mm. Base depth levels are also more consistent in the post-processed data and indeed we would expect to see little cyclical or trend variation in this 4.00 a.m. to 6.00 a.m. period. Table 3.4 shows the reduction in trend for each data set when temperature corrections are applied.

Table 3.4: Resultant change in trend of depth data sets when recorded values are corrected for temperature variations.

Study Period	Recorded Depth		Temperature Corrected Depth	
	Trend (mm/day)	Cumulative Change (mm)	Trend (mm/day)	Cumulative change (mm)
Baseline study	-0.19	-5.84	0.11	3.46
Main study	-0.26	-12.36	-0.09	-4.06
Follow-up study	-0.21	-6.64	-0.23	-3.89

Calibration errors

It was seen in Equation 3.5 that one part of the uncertainty in depth measurements comes from errors in the determining initial depth, which occurs during calibration of the instrument.

These errors are systematic, as each subsequent depth measurement relies on the first measurement (Equation 3.3), and are localised to each study period. This is because the meter used to record flow in this study is portable, and due to limitations on battery life, could not be left *in situ* throughout the study. An error in calibration would therefore not necessarily be consistent throughout all study periods, showing up instead as disparities between the individual data sets.

Physical difficulties in supplying the logger with an accurate depth measurement for calibration, and in securing the sensor, appear to be the sources of this type of error.

The sensor head is at the end of a length of coaxial cable which is held in place above the channel by securing it to a metal ring with cable ties (Figure 3.1). After the cable is secured and initial measurements have been entered, the user is prompted to move the sensor head up and down until a safe height has been reached (Section 3.1.1). It is not always possible for the user to ensure that conditions are the same following setup as they are at the final adjustment of the sensor. The action of holding the cable to move it, for example, can raise or lower the sensor head, or angle it, so that when it is released by the user after calibration, the head can shift, resulting in the logger having incorrect information about its location.

In order to ensure that the logger was given an accurate depth measurement at calibration, a

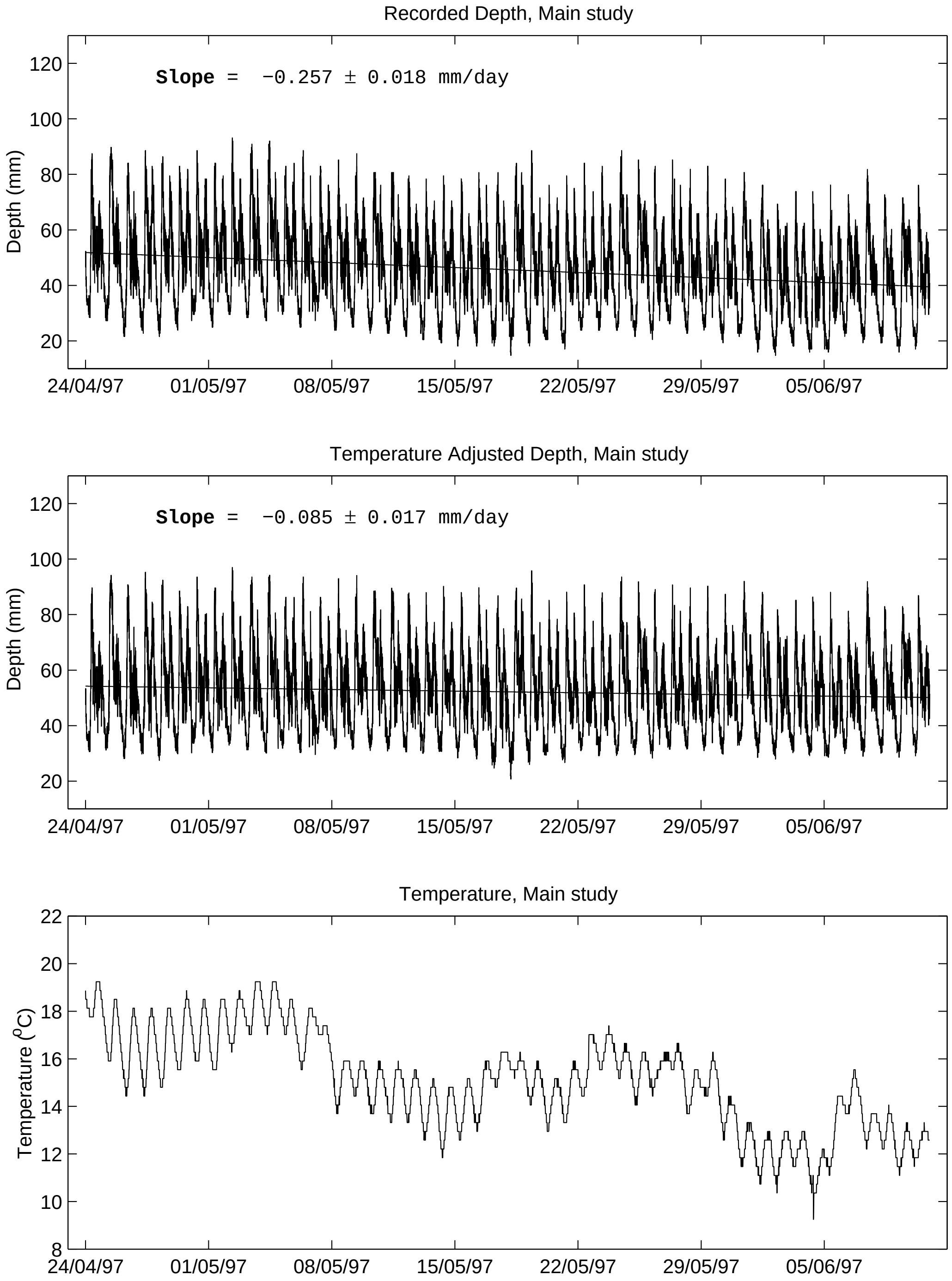

Figure 3.5: Recorded depth values for the Main study, the corresponding temperature adjusted depth and logged temperature values

striker plate of known height was used to form an artificial flow surface (Figure 3.1). The fixed depth of the striker plate is dependent on the inclination of the vertical supporting pole held by the user. Figure 3.6 shows the dimensions of the striker plate, and the resultant change in depth from the centre of the plate, with a support position 5° off vertical. In this particular (arbitrary) example, calibration depth has been entered as being 150 mm, but is actually closer to 142 mm. This type of error would again result in the sensor being higher or lower than its expected location, resulting in all subsequent depth measurements being offset from the actual values by the difference between the expected and actual value of the artificial flow surface.

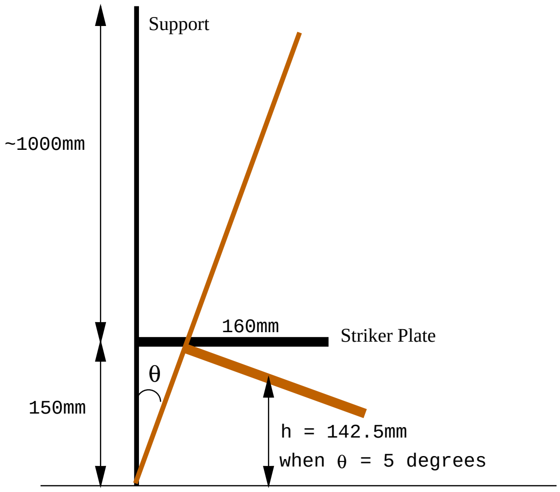

Figure 3.6: Striker plate

This type of error is seen in the raw follow-up study data shown in Figure 3.7. The battery failure and subsequent replacement of the logger resulted in two distinct data sets for this study period. These would be expected to show a strong affinity, the only external factor operating differently on the two records, apart from normal cyclical and trend variations, being the substitution and resultant re-calibration of the logger and sensor.

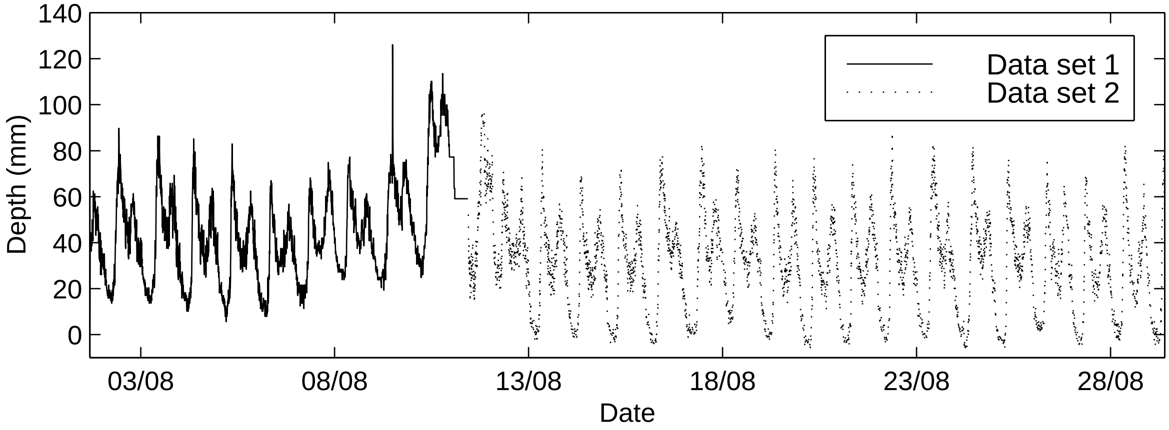

Figure 3.7: Recorded depth, Follow-up study

Although there is a small amount of data missing, and some irregular data during the changeover, it is clear that the two sets of data are dissimilar. The earlier period shows an average base depth of around 15 mm, while the latter period has a base of around 0 to -5 mm. Clearly, in the second data set the logger has emerged from the calibration phase with incorrect information about the sensors position (it is not possible to have negative depths), and it believes that the sensor head is lower than it actually is.

These inter-period calibration variances also present as diversity in the base depth values between study periods. The baseline study low flow period shows a depth of around 20 mm, the main study 30mm, and the latter section of the follow-up study -5 mm.

An experiment was conducted at the site in order to analyse the extent of these errors. The sensor was set up and calibrated over the striker plate by the engineer responsible for setting up the equipment for each study period. Data was logged every five seconds after setup so that changes in depth subsequent to the final calibration adjustments could be seen, with the setup being repeated several times. These results are shown in Figure 3.8. Given no change in conditions between the time a depth of 150 mm is entered into the logger and the time the logger starts recording, we would expect recorded values to be centred around 150 mm, with a small error due to the inherent variability of the measurement system. The variations from the expected depth reading of 150 mm in each case however show clearly that the calibration of the instrument can introduce errors that are large with respect to its precision. None of the tests have an initial recorded depth of 150 mm. Tests two and three, initially measuring 142 mm, have the greatest offset. This initial error could be caused by movement in the striker plate and movement in the sensor head as it is released, both resulting in apparent changes in depth. Subsequent variations would be due only to movement in the striker plate as the sensor head is stationary. As the magnitude of subsequent errors is approximately the same as the initial errors we can conclude that, if the release of the sensor head alters its position in any way, the resultant change in depth is small compared to that caused by variations in the artificial flow surface.

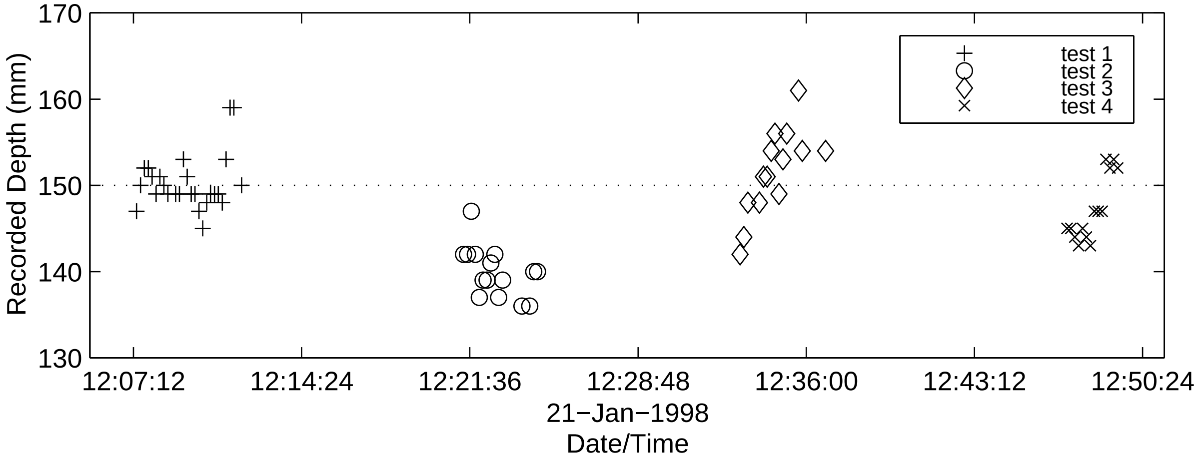

Figure 3.8: Calibration study consisting of four equipment setups over a striker plate of known height (150 mm)

Time and other constraints did not allow for the study conditions to be replicated in the calibration tests. It is therefore possible that several factors influenced the calibration test which could result in more accurate depth readings than would be seen in normally. The tests were conducted sequentially, allowing an accurate repetition of the setup procedure, whereas the setups for collection of the study data spanned six months. If any variation in calibration methods did occur during the study, the offset error caused would not be seen in the tests.

Although the experiments conducted do not necessarily show the upper limit of calibration errors because of the reasons given above, we can use the results along with observations on the available data set to make a reasonable assumption about the error bounds, restricted to this study.

The results in Table 3.5 show the root mean square (RMS) error of the observations.

$$RMS = \sqrt{\frac{\sum r^2}{n}} \tag{3.6}$$

where r are the observation residuals and n is the number of observations.

The residuals are calculated around the expected depth value of 150 mm, so the RMS error represents the magnitude of observation deviation around this known point. This gives us an indication of the possible magnitude of the offset error resulting from calibration factors. The residuals are random errors and are therefore normally distributed, so the RMS of ±6 mm translates to a calibration error bound of ±18 mm.

Table 3.5: Depth measurements obtained using a 150 mm striker plate as an artificial flow surface. The RMS error is calculated around this known depth value.

Trial number	RMS Error (mm)
1	3.1
2	10.5
3	5.1
4	4.6
All data	6.1

Data from other sites can be used to corroborate the above value of the error bounds on depth, and also to identify the particular calibration offset in each study period. The community involved in the Whittlesea trials (Cullen, Heretakis & Herington 1995) was similar to that in Thurgoona, so the data recorded also measured raw sewage made up mostly of domestic waste. Base flows here were around 0.0036 ML/hr for 425 homes. This translates to 0.003 ML/hr for the 356 occupied homes in the Thurgoona study. It is feasible to assume that the base flow for Thurgoona is less than this figure, as the Whittlesea data shows evidence of shift work (a local flow maximum at 3.00 a.m.), that is not evident in Albury.

Table 3.6 lists the average base flow for each period in the Thurgoona study. The data from both the main study and follow-up study base flow do not comply with expected bounds. Given that we would not expect base flows to change significantly, if at all, over the time period in question, it is likely that these apparent shifts in base flow are due to calibration errors. The main study period has an average base flow of 0.0041 ML/hr, which is considerably above the estimated upper limit for this value calculated from the Whittlesea data. The follow-up study low flow value of 0.0 ML/hr is not feasible, and examination of this data shows negative depths, clear evidence of a calibration error, as it is not possible to have negative depths. The mean base flow for the baseline study period however, is positive, and within the proposed upper limit, so it appears that this data suffers from much smaller calibration errors than both other data sets, and is possibly an indication of the true flow pattern for this community.

Table 3.6: Mean daily and base temperature corrected flows

Study period	Mean base flow (ML/hr)		Mean daily flow (ML/day)	
	Measured	Expected	Measured	Expected
Baseline study	0.0008	< 0.003	0.240	≈ 0.260
Main study	0.0041		0.340	
Follow-up study	0.0000		0.130	

Information from the Albury sewage treatment plant (STP) can also be used to confirm the expected flow at Thurgoona. Plant influent measures 16.5 ML/day for this area, which is comprised of domestic dwelling and industry in the ratio 4:1. Influent volume of 13.2 ML/day can therefore be attributed to domestic sources, giving an average of 733 L/day per household for the 18,000 dwellings in Albury. Based on this average, the expected sewage output for the 356 homes in the study area is 0.261 ML/day.

Table 3.6 lists the average daily flow for each period in the study. The expected daily flow calculated above from known behaviour of the Albury community is very close to the mean daily flow of the baseline study. As with the base flow data, the main study period shows a much higher daily flow than expected, indicating that the data set has been shifted in the positive direction. In contrast, the follow-up study daily flows are much less than the average as a result of the data being shifted in the negative direction.

From these comparisons with data from the Whittlesea trials and Albury STP flows, we can surmise that the flow patterns seen in the baseline study period are indeed characteristic of the community under study. The base flow offsets between this period and the main study and follow-up study periods correspond to shifts in base depth of 16 mm for the main study and -17 mm for the follow-up study. The two figures are within the calibration error bounds estimated previously, ± 18 mm, but the probability of obtaining values at close to these limits is very small. This suggests that the calibration test has not replicated field conditions well enough to model all errors in the setup procedure, however it has clearly shown the existence of offset errors.

The identification of calibration errors in the data sets allows us to correct for these offsets in depth values before flow is determined. The previous comparison of base and daily flows with expected values gained from other data sets identified the baseline study data as being representative of the community under study. The constant calibration error in the remaining data sets can be estimated by differencing their mean base depths and the baseline study base depth, and this offset is then removed from all data in each set, resulting in depth readings that are free from, or have much reduced, calibration errors.

Timing errors

Unlike the systematic errors seen previously in calibration, timing errors are random and regular throughout the data set. Errors in the measurement of depth due to timing considerations are expected to be very small. The logger operates at an effective clock frequency of 1.228 MHz, with the minimum resolution being four clock cycles. This translates to a resolution of ± 1.136 mm in the measurement of depth at the adopted velocity of 348.8 m/s.

3.1.3 Calculation of flow from depth

Manning's equation is used to calculate flow in wastewater engineering, especially when grade information is available

$$Q = \frac{AR^{\frac{2}{3}}S_o^{\frac{1}{2}}}{n} \tag{3.7}$$

where

Q is the flow in m^3/s
S_0 is the pipe slope
n, the roughness coefficient = 0.013 for a concrete pipe
R, the hydraulic mean depth = A/P, where P is the wetted perimeter (figure 3.9)
A is the cross sectional area of the pipe.

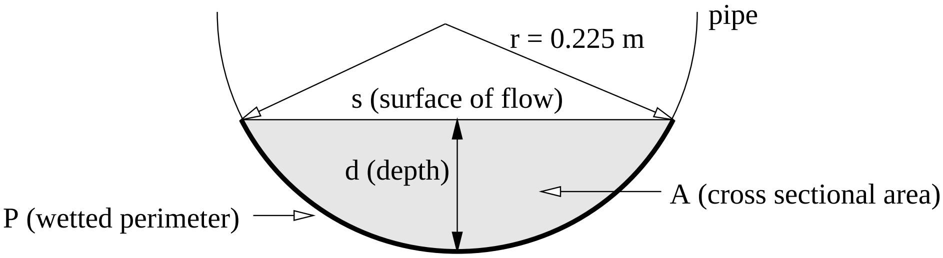

Figure 3.9: Pipe profile

3.1.4 Error bounds on flow measurement

The discussion of depth observations has identified several types of error associated with this experiment. Systematic error contains a local component arising from the calibration process, that manifests as a constant offset to depth measurements. Also contributing to the total systematic error, and again localised to each study period, is the temperature induced variation in the velocity of sound. This is seen not as a constant offset, but as both a cyclical component resulting from the normal daily temperature cycle and a trend component corresponding to seasonal shifts in average temperature. Temperature induced errors are corrected in post-processing (Section 3.1.2), as are calibration errors (Section 3.1.2).

The error arising from temperature variation is related to the precision of temperature measurements and our ability to determine the reference temperature and relate subsequent temperatures back to it. Since it is possible to correct for temperature differences over 0.4°C, and the initial temperature was also expected to be around this figure, residual temperature induced errors in flow are considered small.

The error bounds determined from our knowledge of systematic calibration errors in each period are, however, much less precise. It was demonstrated that community habits are able to place limits on flow, particularly the base flow and total flow per day, and calibration error was reduced by ensuring that measured flow was within these limits. Residual error remains, the magnitude of which can be determined from the range of offset that, when added to depth measurements, results in flow that is still within the determined limits.

The lower bound for offset error in the negative direction is −6 mm. Any greater offset causes negative depths. Turning to daily flow, and error range of ±2 mm allows both the baseline study and the follow-up study data to take on the approximate expected value of 0.26 ML/day. This is not the case for the main study data, which has a lower daily flow, however it is proposed (Section 4.1) that either the community's water usage habits changed during these periods, or an unidentified error is present in the flow data. Taking all information into consideration, placing an error limit of ±6 mm on depth (three times the variation determined in the baseline study and follow-up study data) should ensure that all of the data falls within these bounds.

Figure 3.10 shows how this depth error bound applies to flow. The flow data used represents the average daily flow in the baseline study period. Absolute error is smallest for the lowest flows, however this is also the largest proportional error. For example, the error range at the time of lowest flow (0.001 ML/hr) is 0.0017, or 170% of flow value. At the time of highest flow (0.024 ML/hr), the error range is 0.0085 ML/hr, a much bigger value, but it represents only 36% of the flow.

The proportion of error is quite large and in hindsight it is recognised that a smaller cross-section pipe would have been more appropriate for the study conditions experienced, giving a smaller error to flow ratio.

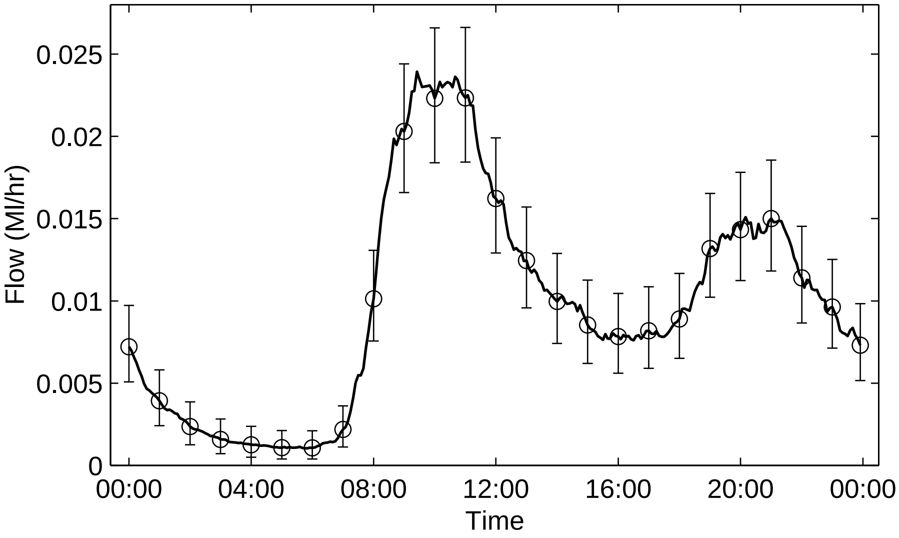

Figure 3.10: Error bounds on average flow when depth errors are ±6.0 mm

3.2 Phosphorus concentration

3.2.1 Sampling procedure

Phosphorus concentration is a point quantity, expressed in mg/L. Samples were taken using a Sigma Streamline portable sampler from an access manhole 25 metres downstream of the flow logger (Figure A.2). The sampler removed 150 mL of liquid from the channel every 40 minutes, and stored three of these samples in one 600 mL bottle, resulting in 12 temporally averaged samples per day.

The process for recovering intermediate values from this bulked sample are described in Section 3.2.4.

The chemistry logger was checked up to three times a day during the study periods to remove obstructions from around the probe that extracts samples from the channel. The probe is partially protected by an outer covering, but is still prone to blockages, particularly when the flow is slow moving and turbid. These occasional blockages resulted in some data loss and post-processing was needed in order to estimate these missing values. The Nyquist sampling theorem states that to ensure no loss of information, the sampling frequency must be twice that of the maximum frequency.

$$f_s \geq 2 \times f_m \tag{3.8}$$

where f_m is the maximum frequency, and f_s is the sampling frequency.

Frequency analysis of the chemistry data showed only a diurnal signal, so a maximum frequency of 24 hours was used to derive the Nyquist sampling frequency, $f_s = 12$ hrs. Gaps in the data that span 12 hours or less were therefore estimated by fitting a polynomial to the data at the endpoints of the gap, without the loss of information from the daily chemistry signal. A different approach was needed to estimate missing data of more than 12 hours. In these cases, the average concentration of bulked samples, evaluated at each sample time, was substituted for the missing data.

3.2.2 Sample analysis

To ensure the integrity of test results and to ease the analytical workload, two laboratories were used to analyse the samples. The first, the CRC for Freshwater Ecology's (CRCFE) Thurgoona laboratory, is accredited by the National Association of Testing Authorities Australia (NATA) to determine the concentration of phosphorus in waters. The second, Albury City Council (ACC) laboratory, uses standard procedures and quality controls but is not accredited.

Samples were retrieved from the automatic sampler each day between 8.40 a.m. and 9.20 a.m. and then transported to the ACC laboratory where they were blended for one minute using a *Waring Commercial Laboratory blender* and stored in a frozen state without additions. Half the samples (those from alternate days) were sent in a frozen state to the CRCFE Thurgoona laboratory for analysis.

Sample preparation, ACC laboratory

Samples were analysed for total phosphorus at the ACC Laboratory using an acidic digestion method. Samples were diluted into the measurement range and digested by adding sulphuric acid solution and potassium persulphate, followed by heating in a *Siltex* autoclave at 98 to 137 kPa for 30 minutes. This digestion procedure was used to convert all forms of phosphorus into an orthophosphate form which could be measured colormetrically (APHA 1995, sec. 4500-P B5).

Sample analysis, ACC laboratory

Samples were analysed by automated ascorbic acid reduction using a *Technicon AutoAnalyzer II* continuous flow system (APHA 1995, sec. 4500-P F).

Sample preparation, CRCFE laboratory

The CRCFE laboratory used an alkaline digestion method to measure total phosphorus. Samples were digested by adding an oxidising reagent composed of potassium persulfate and sodium hydroxide, followed by autoclaving at 120°C for one hour. This digestion procedure converts phosphorus into orthophosphate for measurement colormetrically (Hosomi 1986).

Sample analysis, CRCFE laboratory

Samples were analysed by an automated ascorbic acid-molybdate method using a *Lachat 8000* flow injection analyser (Murphy & Riley 1962).

3.2.3 Inter-laboratory tests

Several inter-laboratory comparison analysis were carried out during and after the study to determine any statistical significance in the difference between the results generated by both laboratories. The results of these analysis, where both labs analysed the same samples, are shown in Figure 3.11. Three analysis runs occurred during the study in the baseline and follow-up periods. These are samples numbered 1 to 29. One analysis followed the study on different, less varying data. These are samples 30 to 42.

It is clear that results from the two laboratories are statistically different. A statistical t-test on the data in Figure 3.11 rejects the hypothesis that the mean of residuals is zero, implying a systematic error. A combination of residuals from all tests yields a mean residual value of 0.4 mg/L, which translates to an average difference of 4.6% between the chemistry data sets from the two labs (the average concentration is 8.7 mg/L). This is perhaps not too surprising as the procedures and tests of the two laboratories are different. The alkaline persulphate digestion method used by the CRCFE (Hosomi 1986) is known to underestimate total phosphorus in

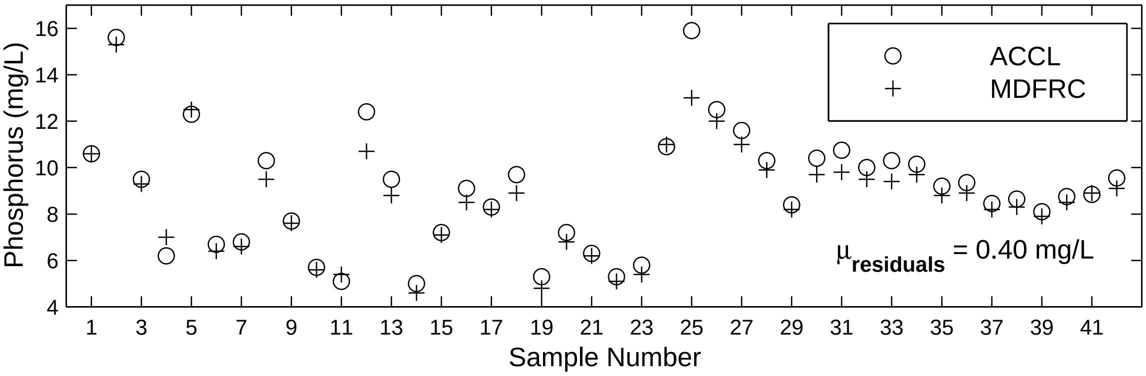

Figure 3.11: Inter-laboratory chemistry comparisons

turbid water (Maher B 1998, pers comm, Sep 3) and this is indeed the effect seen in the inter-laboratory comparisons, where the concentrations determined by the CRCFE are, on average, 0.4 mg/L less than those determined by the ACC.

This difference is recognised by NATA, who regularly distribute reference material samples. Around 20 water quality laboratories participate in the analysis of the NATA reference material samples. In the case of total phosphorus, the reference sample, C has a concentration of 2.02 mg/L. The long term standard deviation on analysis of this sample is 0.17 mg/L, translating to a 95% confidence interval of $1.68 < C < 2.36$. Expressed as percentage change this is ±16.8%. The average long term difference between ACC and CRCFE seen in this study, 4.6% is well inside the 95% confidence region for inter-laboratory tests. The maximum proportional difference seen, 15.9% (not including the one obvious outlier), is also within this 95% confidence region. Any impact of this variation is lessened by the staggered analysis patterns used.

3.2.4 Deconvolution of bulked chemistry data

The chemistry data is comprised of 36 samples per day, taken at 40 minute intervals, $x_1, \ldots, x_{36}$. These are bulked into 12 samples, $b_1, \ldots, b_{12}$, shown in Table 3.7.

We can recover the value of the middle sample $\hat{x}_i$ from the bulked set of three samples $x_{i-1} + x_i + x_{i+1}$ by the following deconvolution process.

The Taylor series expansion for estimating the value of a function $f(t)$ at the point $t + h$ is

$$f(t+h) = f(t) + hf'(t) + \frac{h^2}{2!}f''(t) + \ldots$$

Provided the derivatives $f^{(n)}(t)$ exist, we can characterise the three temporally sampled data in the bulked value with a three term Taylor series.

$$\begin{array}{lcll} x_{i-1} & = & f(t-h) & = f(t) - hf'(t) + \frac{h^2}{2!}f''(t) \\ x_i & = & f(t) & = f(t) \\ x_{i+1} & = & f(t+h) & = f(t) + hf'(t) + \frac{h^2}{2!}f''(t) \end{array}$$

Table 3.7: Chemistry sampling times

Bottle Number	Sample Times	Bottle Number	Sample Times
Bottle 1	01:20 02:00 02:40	Bottle 7	13:20 14:00 14:40
Bottle 2	03:20 04:00 04:40	Bottle 8	15:20 16:00 16:40
Bottle 3	05:20 06:00 06:40	Bottle 9	17:20 18:00 18:40
Bottle 4	07:20 08:00 08:40	Bottle 10	19:20 20:00 20:40
Bottle 5	09:20 10:00 10:40	Bottle 11	21:20 22:00 22:40
Bottle 6	11:20 12:00 12:40	Bottle 12	23:20 00:00 00:40

Adding these values and rearranging gives

$$f(t) = \frac{f(t-h) + f(t) + f(t+h)}{3} - \frac{1}{3}h^2 f''(t)$$

The first term represents the temporal average, $\overline{x}$, of a sequence of n observations

$$\overline{x} = \frac{1}{n}\sum_{i=1}^{n} x_i \tag{3.9}$$

while the last term represents a correction to be applied to the sample mean.

So we now have

$$x_i = f(t) = \overline{x} - \frac{1}{3}h^2 f''(t) \tag{3.10}$$

The level of recovery of x_i is dependent on the ability of the Taylor series to model the processes occurring. In particular the validity of a continuous first differential and the existence of the second differential. Thus in reality we only obtain an approximation of x_i.

Estimates of the first and second order derivatives can be derived by piecewise fitting a second order polynomial to the bulked data. With this information, an estimate of the value at the centre of the sampling period $\hat{x}_i$ can be obtained.

In this process of estimating the original unbulked data from the bulked values, information is lost at the first and last data points in each set. The derivation of second order differential for each bulked value b_j requires two adjacent data points, b_{j-1} and b_{j+1}, which are not available for b_1 and b_n, hence the range of useable data is two hours less at either end than the originally collected samples.

$$\hat{x}_i = \overline{x} - \frac{1}{3}h^2 X_i''(t) \tag{3.11}$$

where $h = \frac{1}{3}$, taking the space between each bulked data point to have a value of 1 (Figure 3.12).

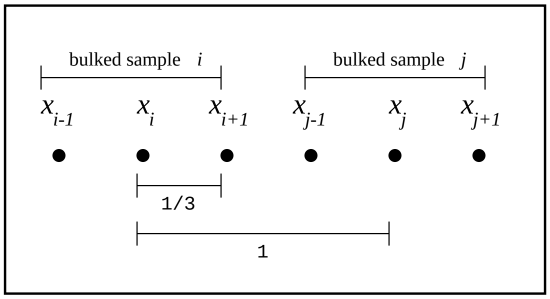

Figure 3.12: Value of spacing between bulked data points

In the final stage of the recovery of the original data set, the values between each sample $\hat{x}_i$ are estimated by curve fitting. A cubic curve is used to model the data between each $\hat{x}_i$ and $\hat{x}_j$, because they are the lowest order representation of curve segments that allows the end of the segments to pass through the given points ($\hat{x}_i$'s) while providing continuity of slope and position where the segments meet.

The first order differential information available for each data point can be used to improve the accuracy of the resultant fit by constraining the slope of the curve at and between each $\hat{x}_i$. The Bezier form for defining a cubic makes use of this additional derivative information, and provides the above-mentioned continuity of slope and position, and so is a suitable choice for the recovery of intermediate data points. The Bezier cubic is a parametric curve, where the x and y components are each represented as a third-order polynomial of a parameter t.

$$\begin{array}{rcl} x(t) & = & a_x t^3 + b_x t^2 + c_x t + d_x \quad ,0 \le t \le 1 \\ y(t) & = & a_y t^3 + b_y t^2 + c_y t + d_y \end{array} \tag{3.12}$$

It has solutions of the form

$$P(t) = T \cdot M_b \cdot \begin{bmatrix} P_1 \\ P_2 \\ P_3 \\ P_4 \end{bmatrix} \tag{3.13}$$

where

T is a vector of the parameter $t = \begin{bmatrix} t^3 & t^2 & t & 1 \end{bmatrix}$
M_b is the Bezier matrix, a known 4×4 constant matrix.
$P(t)$ contains both the $x(t)$ and $y(t)$ components
P_1 and P_4 are adjacent recovered $\hat{x}_i$ values.

The values P_2 and P_3 are known as *wing points* and are derived using the available differential information

$$P_2 = P_1 + \frac{1}{3} S_1 \tag{3.14}$$

$$P_3 = P_4 - \frac{1}{3} S_4 \tag{3.15}$$

where S_1 and S_4 are the derivative information X_i', the slope at P_1 and P_4.

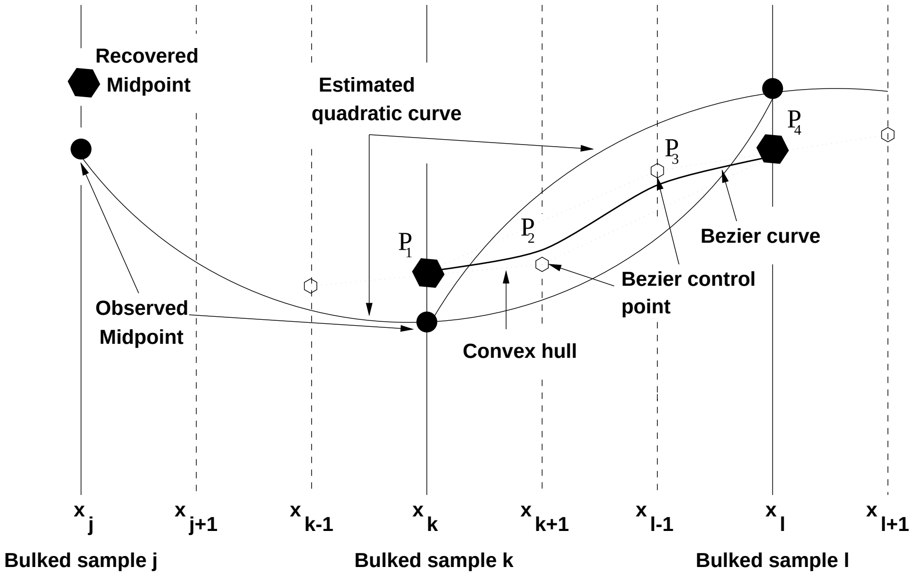

Figure 3.13: Bezier curve

Diagram 3.13 shows an example of a Bezier curve and its four control points. The dotted line shows the convex hull that bounds the Bezier curve. During this part of the recovery process further data is lost, as the samples outside the two outer recovered midpoints cannot be calculated with the Bezier algorithm. (Figure 3.14).

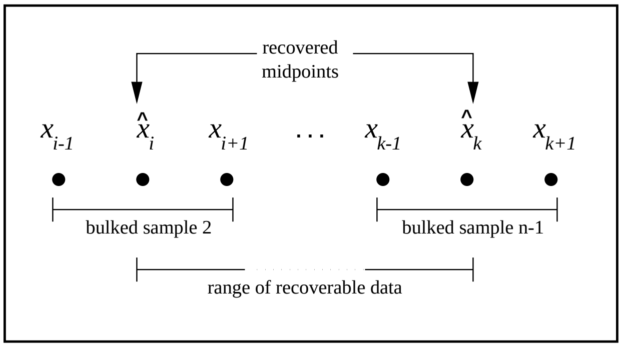

Figure 3.14: Recoverable data from the bulked data set

In summary, we have started with the set of bulked, or temporally averaged, phosphorus concentration data $b_1, b_2, \ldots, b_j, \ldots, b_n$ where each b_j is comprised of three samples $x_{i-1} + x_i + x_{i+1}$ taken at 40 minute intervals. The bulked values b_j are then corrected according to

Equation 3.11 to produce an estimate of the central value $\hat{x}_i$. The final two control points for the Bezier curve, the wing points, are evaluated relative to this corrected point using the slope of the fitted function, X_i'. This ensures continuity of the first derivative at the recovered points. Bezier curves are then calculated over the whole data set, giving values for the intermediate phosphorus concentrations.

3.2.5 Error bounds

The precision of chemistry measurements is restricted by the resolution of the measurement technique. Quality control data provided by ACC showed that the concentration of a known sample (theoretical concentration, $C = 0.326$ mg/L) analysed with the 1:25 diluted unknown samples from the Thurgoona sewer, was kept within a limit of the theoretical concentration $C \pm 0.024$ mg/L. The concentrations derived for the unknown samples are therefore kept within the limits ±0.6 mg/L, which represent a ±7% error on average chemistry data. These errors, by their definition, are random throughout all chemistry data sets.

The allowed error bound on control samples C_n to C_{n+20} are calculated from the standard deviation of the measured concentration of the previous 20 control samples

$$\begin{aligned} UCL &= \mu + 3\sigma \\ LCL &= \mu - 3\sigma \end{aligned} \tag{3.16}$$

where

μ is the mean of the previous 20 control samples
σ is the standard deviation of the previous 20 control samples
UCL is the upper control limit
LCL is the lower control limit.

The above error limit of ±0.6 mg/L may therefore vary slightly over all the Thurgoona data analysed at ACC, and may not be symmetric, but is sufficient for this calculation of random errors. The CRCFE laboratory also applies quality control around similar limits, so the above limits can be used to discuss error bounds over the whole data set.

The total error bounds for concentration are therefore comprised of a systematic component of up to 0.4 mg/L, and a fluctuating component varying between the limits ±0.6 mg/L. From these values, the maximum error that could be expected is ±1.0 mg/L, so this figure will be used to describe error bounds on the measurement of concentration. This represents a ±7% error on average total phosphorus data.

3.3 Social Survey

The participants in the Thurgoona Case Study were surveyed on two occasions. The first, the pre study questionnaire (Appendix E), was conducted on April 9-11 before the phosphorus-free detergent usage. This survey was concerned with study logistics, such as the willingness of the residents to participate in the study, and the amount and type of detergent they required for the six weeks, and with gaining information about the regular, or baseline, washing habits of participants. The second, the post study questionnaire (Appendix F), was conducted on the week beginning June 16 when participants were again supplying and using their own detergent. This survey collected information on the level of awareness of the effect of phosphorus in waterways and of phosphorus-free products, satisfaction with the phosphorus-free products, and on laundry washing habits and household makeup during the study period. The information on laundry washing habits and household logistics is of most interest in this report as it can be used to examine the correlation between phosphorus load in sewage and laundry usage patterns. A summary of some of this information is given below.

Figure 3.15 shows a breakdown of the days that households do their laundry washing. These percentages do not take into account the amount of washing that is done, simply the day it is done. The data clearly shows Saturday to be the most popular wash day, with 72% of participants washing on this day, while Tuesday and Thursday are the least popular.

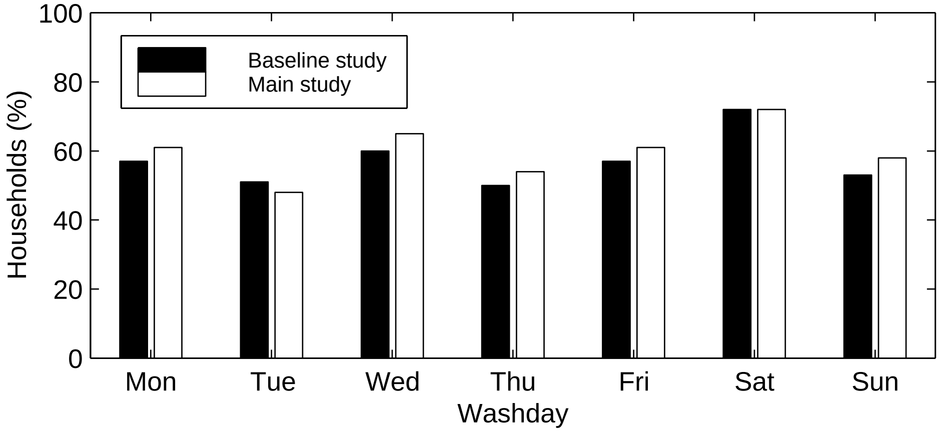

Figure 3.15: Households that wash each day

The proportion of the total number of weekly washes done each day is shown in Figure 3.16. These percentages relate most directly to the measured phosphorus load data. There are differences in the daily breakdown of washing between the baseline study and main study periods, but a general pattern remains that shows three distinct groups of washing days. The first group, Saturday, has the highest proportion of washing. The mid group is made up of Monday, Wednesday, Friday and Sunday and represents a moderate amount of washing. The last group, Tuesday and Thursday, has the least amount of washing.

Table 3.8 shows the average number of washes per household per week. As with the previous data, there is a difference between the main study and baseline study periods. The small increase in the number of washes per week during the main study period is also indicated in the second survey, where 18% of respondents stated that they had done extra washing during the main study period. The majority of this extra washing was attributed to two causes, cleaning up after holidays, 8%, and washing of blankets, curtains and other manchester, 6%, possibly to make use of the free laundry detergent.

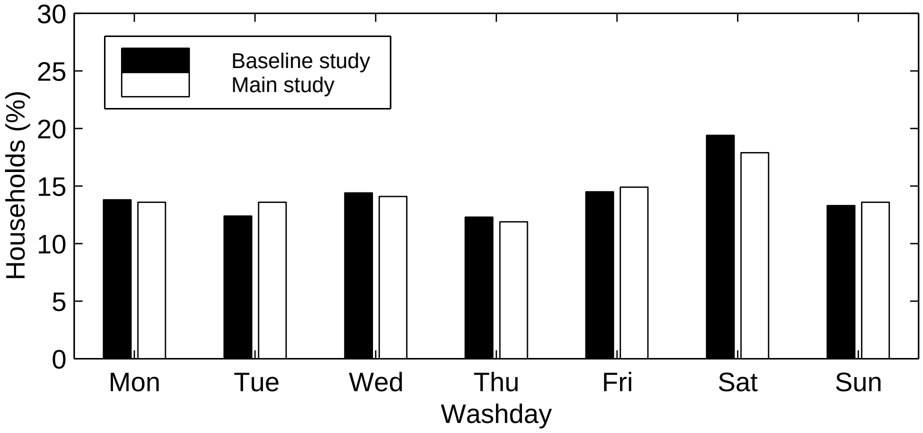

Figure 3.16: Total weekly washes per day

Table 3.8: Average number of washes per household per week

Study period	Washes per week
Baseline study	9.74
Main study	9.97

Table 3.9 shows the time of day that study participants do their washing. Most households, 70-75%, wash primarily in the morning, with the remainder distributed fairly evenly over afternoon, evening and night. It should be noted that participants were permitted to select only one option in answering this question, so the figures given represent the time of day that most washing is done. In reality people may not always wash at the same time of the day.

Table 3.9: Time of day that study participants do their washing.

Study period	Time of day				
	Morning	Afternoon	Evening	Night	Unknown
Baseline study	74%	8%	8%	5%	5%
Main study	70%	11%	11%	5%	3%

Table 3.10 shows the primary type of detergent used by study participants before the distribution of phosphorus-free detergent. Usage of detergents is classified by the level of phosphorus in the detergent. An explanation of the classifications follows.

Table 3.10: Primary household detergent usage by study participants before main study, classified by level of phosphorus

Detergent type	Usage
NP	23%
P	67%
No limit	7%
Unknown	8%

NP The product contains no added phosphorus. Levels below 0.5% may be present.

P The product complies with agreed Australian industry standard. Phosphorus levels must be below 7.8 grams per wash.

No Limit No statement about phosphorus level is made on product.

Phosphorus-free detergent was already being used by 23% of the participants before the study was carried out. A decrease in phosphorus load during the main study is therefore representative of the amount phosphorus can be reduced in a community, a quarter of whom are already using phosphorus-free detergent. The potential decrease in load would be higher if a larger proportion of the community normally used detergent with added phosphorus.

Information from the pre-study questionnaire can be used to gauge the level of participation of those households receiving phosphorus-free detergent. Table 3.11 shows a breakdown of the detergent usage of participants during the main study. Only 21 (9%) of participants used any detergent other than the free NP detergent supplied by Albury City Council, and 5 (2%) of those used other phosphorus-free detergents, leaving only 7% of participants contributing phosphorus from laundry washing. Given this small number of households, and the fact that they still used the free NP detergent most of the time, we can assume that the amount of phosphorus generated from laundry detergent by the study participants during the main study period is negligible.

Table 3.11: Primary household detergent usage by study participants during main study, classified by level of phosphorus

Detergent type	Usage
Free NP detergent	91%
Free NP detergent plus other:	
NP detergent	2%
P detergent	4%
No limit	3%

To further confirm that the effect of phosphorus produced as a laundry by-product by participants during the study is negligible, we can look at the times during the study that detergents containing phosphorus were used. These times are shown in Table 3.12. The figures are fairly well spread, with six respondents using P detergent throughout the study, and only five starting usage at the end of the study. This small figure means that we should not see any trend associated with the take-up of P detergent in weeks five and six of the study.

Table 3.12: Usage of detergents containing added phosphorus during the main study

Time During Study	Number of households
Throughout	6
Beginning	0
Middle	1
End	5
No response	4

Useful for characterising the community under study, enabling future comparisons of load data, is household logistics. Table 3.13 shows summary data concerning the number of household in the study, and the makeup of those households.

Table 3.13: Study community and household makeup

Characteristic	Value
Number of households in	
catchment	357
study	227
People per household during	
baseline study	3.49
main study	3.50

Chapter 4

Data analysis

This section looks at the processed and error corrected flow and phosphorus data. The data for each study period is examined and characteristics noted and the calculation of phosphorus load is explained.

4.1 Flow

Flow characteristics

Corrected flow data for each of the three study periods is shown in Appendix B. These time series plots show the following major characteristics of the flow:

1. The minimum or base flow is near zero (around 0.0008 ML/hr) and occurs between 4 a.m. and 6 a.m.
2. The maximum flow occurs mid-morning. This maximum value varies according to both the study period, and the day of the week.
3. A second, less intense, maximum occurs in the evening.
4. The mid-afternoon is a period of declining flow with the minimum reached around 4 p.m.
5. The average flow time needed to transport the household effluent to the sampling point is close to one hour.

Frequency analysis of the data also shows the diurnal and semi-diurnal signals noted above, with the semi-diurnal term dominating.

These general characteristics are controlled by the Thurgoona community's water usage patterns. For example, the social survey data shows that around 70% of study participants do their laundry washing primarily in the morning (Table 3.9), which corresponds with the morning peak in flow. Community habits also control variations in flow between days of the week. Figures C.2 and C.5 highlight this variability in a sequence of plots illustrating the average flow characteristics for each day of the week. The significant variations that these figures show are:

1. The nature and time of the early morning flow onset. For weekdays this is around 6 a.m. while for Saturday and Sunday it is an hour or two later.
2. The height and width of the weekday peaks compared to the weekend peaks.
3. The mid-afternoon low. This tends to be higher on weekends, particularly on Sunday.

Flow can also be characterised on a per period basis. Two characteristics, base flow and daily flow, are shown in Table 4.1. Base flows are very similar in each data set. This is expected as calibration errors were reduced by aligning base flows.

Table 4.1: Average flow characteristics

Study period	Average flow characteristics	
	Base flow ML/hr	Daily flow ML/day
Baseline study	0.00084	0.24
Main Study	0.00075	0.17
Follow-up study	0.00074	0.27

A comparison of average daily flows shows a dissimilarity between the data sets. The main study has the lowest mean daily flow, 0.17 ML/day compared to 0.24 ML/day in the baseline study and 0.27 ML/day in the follow-up study. Figures B.1 to B.3 show that the daily signal in the main study data set has a smaller peak amplitude which is reflected in the average daily values. This difference in the peak magnitude of the main study period flow could be explained by a change in the community's water usage habits, or by errors in the depth data.

Results of the social survey do not indicate any significant change in the amount of washing done by study participants between the baseline study and the main study periods (Section 3.3). If anything, a small increase in the number of loads of washing is indicated. It is possible though that the community, while carrying out the same amount of washing, practiced water conservation, which is part of the overall strategy. Indeed an in-depth study of flow into the Albury treatment works determined that over the last eight years, despite increases in population and industry, that there has been no net increase in flow. The practice of using full laundry loads is believed to be a significant contributor to this flow reduction, along with other *waterwise* practices.

If the change in this data set were the result of a calibration, or constant offset error alone, peak flows should rise in accordance with a base flow rise. An examination of the original depth data however shows that the higher the base flow of the data set, the smaller the peak amplitude. A non-linear effect like this could come from an incorrect velocity value, or a malfunction in the circuitry that places an error in the determined depth. As the depth increases this error grows. This could cause a difference in behaviour between the different loggers. Albury City Council has a number of these portable flow loggers, and although it is known that the same logger was not used for data collected in all study periods, it is not know which was used to collect each data set, or when changes took place. Other factors that should be considered relate to normal limitations of the logger, such as the directionality of the ultrasonic pulse, and to the effect the sewer environment has on the returning signal, particularly as related to the height of the sensor.

In order to accommodate the possibilities of both changes in water usage and an existing error in the data, the change in the amount of phosphorus in the community's effluent can be examined in terms of the change due to flow, and the changes in phosphorus concentration. This is explored further, and results given, in Section 4.3 and Chapter 5.

Data loss

During the follow-up study, a low battery voltage necessitated the replacement of the logger. This occurred on August 11 at 10:20 a.m., nine days after flow data logging commenced for this period. In the changeover time, four discrete data values were lost, and logging began again at 10.45 a.m. The day of the battery failure and the following two days show data that is out of the ordinary. Peak flows increase by one third, base depths increase markedly and the identifiable daily flow pattern is not apparent. It is unlikely that the low battery voltage or a logger fault is responsible for the anomalous data, as the flow is high both sides of the changeover point when the logger was replaced.

A temporary increase in depth can be caused by a blockage in the pipe, and it has been proposed that this is the effect seen in the follow-up study data. This, however, appears unlikely. The sewerage system is relatively new, and is composed of low friction pipes with a grade of 1:500, so the probability of anything lodging in the pipe is low. The chemistry sampler was located 25 m downstream from the flow logger, and was invasive in that a probe rested on the bottom of the pipe and was connected by tubing to the sampler above. This probe may have provided an anchor for solid matter thus causing a blockage, but again it is unlikely. The probe was cleared several times a day during sampling, so any foreign matter would have been removed fairly quickly and would not cause the effect seen over several days. The fall between the flow logger and the chemistry sampler is 50 mm so an obstruction around the chemistry probe would have to be quite large to increase base depths by 30 mm, and again this is not very likely.

There is indication however that at least some of the anomalous flow is caused by infiltration and inflow from rainfall. Several rainfall events of up to 40 mm per day were recorded around this time, and examination of phosphorus data shows some corresponding dilution of concentration. Due to the difficulties of joining the two data sets, and the four days of anomalous data around this time, it was not possible to use all of the follow-up study data. The period of analysis has therefore been shortened to August 13-25.

4.2 Phosphorus

Phosphorus concentration data for each study period is shown in Figures B.1 to B.3. Frequency analysis of the chemistry data shows a daily signal, which, although not as clear as the daily flow pattern, can still be noted visually. This is most evident in the follow-up study data (Figure B.3) where typically, phosphorus concentration falls to its lowest daily level between 4 a.m. and 6 a.m., coinciding with times of low activity and low flow. During the day there can be several peak concentration times, the most obvious and most regular being a morning peak around 10 a.m. This coincides with maximum water usage, and also with the highest level of laundry washing.

Table 4.2 shows the mean phosphorus concentration for each period. Average concentration has reduced during the period of phosphorus-free detergent usage from a baseline study level of 10 mg/L to just over 8 mg/L. This decrease will, unless accompanied by an increase in flow, contribute to a lower phosphorus load resulting from the use of phosphorus-free detergents. Average phosphorus concentration in the follow-up study period has stayed around the same level as the main study period. If all other conditions remain equal, load will also remain stable between these two periods.

Table 4.2: Mean phosphorus concentration

Study period	Phosphorus (mg/L)
Baseline study	10.01
Main Study	8.28
Follow-up study	8.37

4.3 Load

Load is a measure of how much phosphorus is present in the community's effluent. Phosphorus load is a function of both flow and concentration. It represents the amount (in kg) of phosphorus leaving the study catchment. The usual relationship connecting flow, f, concentration, c and load, l, is

$$l = f \cdot c \tag{4.1}$$

In this study we are interested in changes in the load, δl, caused by changes in the flow, δf and changes in the concentration, δc. The algebraic connection between these finite quantities is

$$\delta l = f \cdot \delta c + c \cdot \delta f + \delta f \cdot \delta c \tag{4.2}$$

There are two additional terms in this equation compared to the commonly used simple model

$$\delta l = f \cdot \delta c \tag{4.3}$$

That is, in addition to changes in the load due to changes in concentration there are also changes due to flow and the second order interaction of these parameters. It is also readily seen that if there is no change to the flow regime, $\delta f = 0$, then equation 4.2 reverts to the simple case of equation 4.3.

Table 4.3 lists the principal changes in both δf and δc and their effect on the second order interaction term. The table also comments on the likely causes of some of these combinations.

It is demonstrated in Table 4.3 that large positive values for the change in concentration, δc, are unlikely to occur as this would represent a change in conditions or assumptions during the study period. However both positive and negative changes in flow are possible and must be considered.

Before applying Equation 4.2, the base level from which change is derived or computed must be considered. Since the Thurgoona study conducted an initial trial to establish a baseline of normal community activity, this must be adopted. However the number of monitoring days in the baseline study period, the main study period and the follow-up period are unequal and hence averaging techniques must be used to define a standard day as well as other intervals of interest. Variation within these average conditions does not effect the data as computed from Equation 4.2 but rather generates a dispersion about the computed values.

Table 4.3: Principal causes of change in flow and concentration and their effect on the second order interaction term

Parameter	Effect on $\delta f \cdot \delta c$	Comments on parameter and effect
$\delta f = 0$	$\delta f \cdot \delta c = 0$	Changes in the flow are non-existent or minimal. This is an ideal situation where the target population doesn't modify its water usage habits and all environmental conditions remain the same.
$\delta c = 0$	$\delta f \cdot \delta c = 0$	Changes in the concentration of total phosphorus are minimal. This is an unrealistic expectation when phosphorus-free detergents are introduced into the community except for the possibility that laundry detergent phosphorus is not a major urban point source.
$\delta f > 0$ and $\delta c > 0$	$\delta f \cdot \delta c > 0$	The flow and phosphorus concentration both increase. Here the positive second order term represents an underestimation of the change in the first order term. It is an unlikely scenario as positive increases in phosphorus concentration, while depleted in the laundry detergent, indicate that the system is not stable or has been subjected to an external perturbation other than a change in laundry patterns.
$\delta f < 0$ and $\delta c < 0$	$\delta f \cdot \delta c > 0$	The flow and phosphorus concentration both decrease. In this case the magnitude of the second order term represents the level of overestimation that is due to reductions in one or both components. This is a likely scenario when usage of phosphorus-free detergents is accompanied by water conservation practices.
$\delta f > 0$ and $\delta c < 0$ or vice versa	$\delta f \cdot \delta c < 0$	One component increases, while the other decreases. In this case the second order term represents an underestimation of the effect of reduced concentration. This is possible with flows increasing due to the availability of free laundry detergent for non-regular washing. Since it is a second order effect the magnitude would be small.

Chapter 5

Results

The results from both the main study and follow-up periods are presented in this section using time and frequency domain analysis methods.

Time domain analysis is the conventional analysis approach. It is concerned with how the function or parameters describing the data, including the mean and standard deviations, change with time. Figures plotting the function or time series relative to a time axis are a common method of performing this analysis although there are many more sophisticated methods. It is to be noted that the mean and standard deviation of a time series are time dependent with the interval over which the averaging is performed playing an important role.

Frequency domain analysis is an alternative approach where time, t, is replaced by frequency. That is the series is no longer represented by time varying quantities but by parameters that describe cosine/sine waves. In particular it is the amplitude, a_i, frequency, ω_i and the phase, ϕ_i of a wave that carry the information. That is

$$x(t) = \sum_{i}^{n} a_i \cos(\omega_i t + \phi_i) \tag{5.1}$$

There are two major approaches that use Equation 5.1. The first and more common approach is the Fourier method (Oppenheim & Schafer 1989), in which average values over the data set are determined. The second is the wavelet approach where the wave information is allowed to vary as a function of time (Strang & Nguyen 1996). Both approaches provide different information and thus will be used in this report.

Results that describe the proportion of phosphorus in laundry detergent as determined by introducing phosphorus-free detergent into the community and measuring this change against the baseline data are described in the following main study section. The average change in phosphorus load due to the use of phosphorus-free detergents in the community is presented and the measured signals described, including daily averages which contain information about the community's habits. The frequency information, which supports and amplifies the time series results is then presented.

Results that describe the medium to long term effects of a phosphorus awareness campaign are presented in the follow-up section.

5.1 Main Study

In the data analysis section, Section 4.3, a multi-part model was developed to describe the load. The results from applying this model to the observed data are presented using time domain plots containing five traces. These traces are:

1. A heavy dashed line representing the load during the baseline study period.
2. A heavy solid line representing the load during the main study period when the community was using phosphorus-free laundry detergent.
3. A light dashed line representing the change in load due to the change in flow, $\delta f \cdot c$. This is calculated using phosphorus concentration from the baseline study period and the change in flow from the baseline study period to the main study period. Positive values are due to an increase in flow while negative values are due to a decrease in flow (Table 4.3).
4. A light solid line representing the change in load due the change in concentration, $f \cdot \delta c$. This is calculated using the flow from the baseline study period and the change in the concentration from the baseline study period to the main study period. Positive values are due to an increase in concentration while negative values are due to a decrease in concentration, see Table 4.3.
5. A light dotted line representing the interaction term, $\delta f \cdot \delta c$, is due to changes in both flow and concentration. The term's sign term is taken from the signs of the two constituents. It is fully described in Table 4.3.

In all cases the abscissa is time with a range of either one day or one week. The ordinate is load uniformly expressed in kg/hr.

5.1.1 Average results

The average reduction in phosphorus load between the baseline study and the main study is shown in Figures 5.1 and 5.2. This amount, 1.18 kg/day, or 47%, represents an upper limit on the amount of reduction, and is due to changes in both flow and phosphorus concentration. It represents a scenario where the measured decrease in flow is correct, possibly due to a change in water usage habits.

In order to accommodate the possibility that the measured changes in flow are due to error, the change in load that is independent of changes in flow, a reduction of 24%, can be cited as a lower limit on phosphorus reduction.

This reduction occurred when the community moved from the baseline state where at least 16% of households used phosphorus-free laundry detergent, to the main campaign where phosphorus-free laundry detergent was used by at least 64% of the community. The results have not been adjusted for that fraction of the community, 36%, which did not take part in the trials nor for that part which already used phosphorus-free detergent. In general the reductions have been obtained by increasing community participation from 16% to 64%, a rise of 48%.

The use of 1.18 kg/day and 0.60 kg/day as upper and lower limits for the reduction in phosphorus load due to the use of phosphorus-free laundry detergents translates, without adjustment, for community participation to a reduction between 56 and 29 kg/day for the whole Albury community. That is the expected influent load at the Albury treatment works would fall from the present average level of about 120 kg/day to a level between 64 and 91 kg/day.

The daily load shows the characteristic double peak signal that was seen in the Whittlesea data, (Cullen, Heretakis & Herington 1995). This double peak has now been identified as being due to the addition of diurnal and semi-diurnal contributions.

Other global/average features and characteristics are:

1. The high level of correlation displayed between the load signals and the reduction signals, showing that the greatest reduction in load occurred at the times of greatest water usage.
2. The correlation between phosphorus reduction and laundry washing times. The greatest reduction occurs during the mid-morning peak, also shown to be the time most laundry washing is done (Table 3.9).
3. The low level of the interaction term when one or both of the change terms are small. This is in-line with the discussion in the above sections and Table 4.3.
4. The lag of the reduction in load due to changes in phosphorus compared to the reduction in load due to changes in flow at the leading edge of the morning peak. It is hypothesised that phosphorus awareness and *waterwise* practices that reduce the amount of water usage, such as full washing machine loads, were being practiced in the community by both study participants and non-participants. The hypothesis that the community adopted *waterwise* practices is discussed in the following section on Monday load patterns.

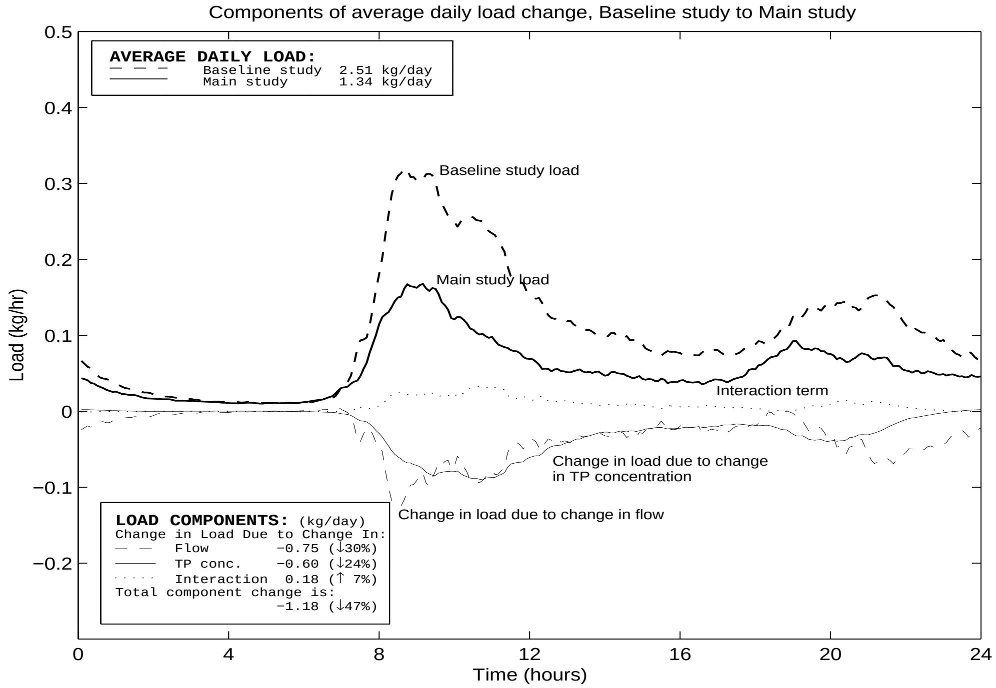

Figure 5.1: Components of average daily load change Baseline study to Main study

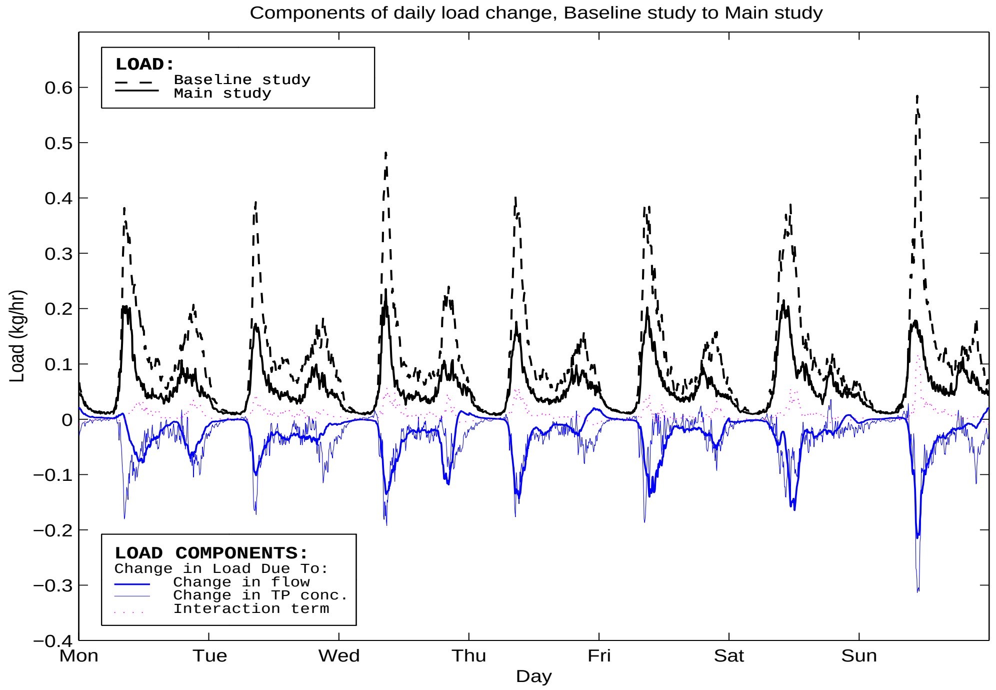

Figure 5.2: Components of daily load change Baseline study to Main study

5.1.2 Daily results

The daily results are shown in Figures 5.3 through 5.9. Each of the days shows behaviour that is consistent with a weekly cycle of household activity. This weekly cycle is evident in Figure 5.2. It is most evident in wavelet decompositions of the signal (Figure 5.12). The weekly cycle of laundry activity is also discussed in the social survey section, Section 3.3.

The average daily load reductions and component changes are also detailed in Table 5.1. The average baseline patterns are computed from three consecutive weekly values while there are seven consecutive values available in the main study period. It was shown in Section 3 that considerable errors exist in the raw observational data, especially the flow data. The random components of these errors are significantly reduced by using large samples. Unfortunately systematic errors are not reduced by averaging. Since it has not been possible to isolate and distinguish all of these errors its has not been possible to provide strict and formally deduced estimates of uncertainty. Rather, it is argued that the approach of upper and lower limits is more appropriate with the upper limit being the reduction that includes both the flow and concentration components while the lower limit is the reduction due to concentration changes only. It shown in Section 3.2 that errors in concentration measurement were random and did not exceed 0.6 mg/L or 7% at the three standard deviation level. Averaging will reduce this value by the square root of the number of observations,

$$\sigma_{\overline{x}} = \frac{\sigma}{\sqrt{n}} \tag{5.2}$$

resulting in the error in concentration being less than 3%, which can be considered negligible compared to errors in flow. Thus the contribution that these errors make to the determined loads and the magnitude of the interaction term is negligible.

Table 5.1: Daily phosphorus load reductions

Week day	Baseline load (kg/day)	Main study loads and components.				
		Total Load (kg/day)	Load Change (kg/day)	Flow Change (kg/day)	Conc. Change (kg/day)	Interaction
Monday	2.61	1.38	-1.23	-0.90	-0.51	0.19
Tuesday	2.42	1.21	-1.21	-0.80	-0.60	0.19
Wednesday	2.66	1.30	-1.36	-0.81	-0.77	0.22
Thursday	2.27	1.22	-1.05	-0.72	-0.47	0.15
Friday	2.37	1.32	-1.05	-0.50	-0.68	0.13
Saturday	2.56	1.47	-1.09	-0.62	-0.62	0.15
Sunday	2.80	1.45	-1.35	-0.93	-0.66	0.24
Average	2.53	1.34	-1.19	-0.75	-0.62	0.18

It is seen from Table 5.1 that the upper limits for the daily reductions have a mean value of -1.19 kg/day. The lower limit of the reduction, the component that is due to changes in phosphorus concentration, is -0.62 kg/day. What is clear is that the each individual day contributes different levels of reductions due to differences in the community's habits.

Monday

A striking feature of Monday's load pattern, Figure 5.3, is the small change in concentration, δc, between 8.00a.m. and 9.00 a.m. which leads to a small $f \cdot \delta c$ term and hence a small interaction term, while the change in load due to flow term, $\delta f \cdot c$, has considerable magnitude. After about 9.00 a.m. the reduction in load due to phosphorus begins to rise, reaching a maximum near 12.00 midday. The interaction term shows the same slow rise to a maximum at this time. It is hypothesised that community activity early on Monday morning is not consistent with a reduction in phosphorus but is consistent with a full load strategy. As the morning progresses the activity is more consistent with a reduced phosphorus environment. This could be due to non-participating households having completed their washing cycles.

Monday evening's patterns are characterised by reduction in load due to both flow and concentration, indicating evening laundry activity. This is consistent with the evening reduction pattern seen also on Wednesdays and Fridays. This is consistent with the social survey data which identified these three days as being the weekdays on which most laundry washing is done.

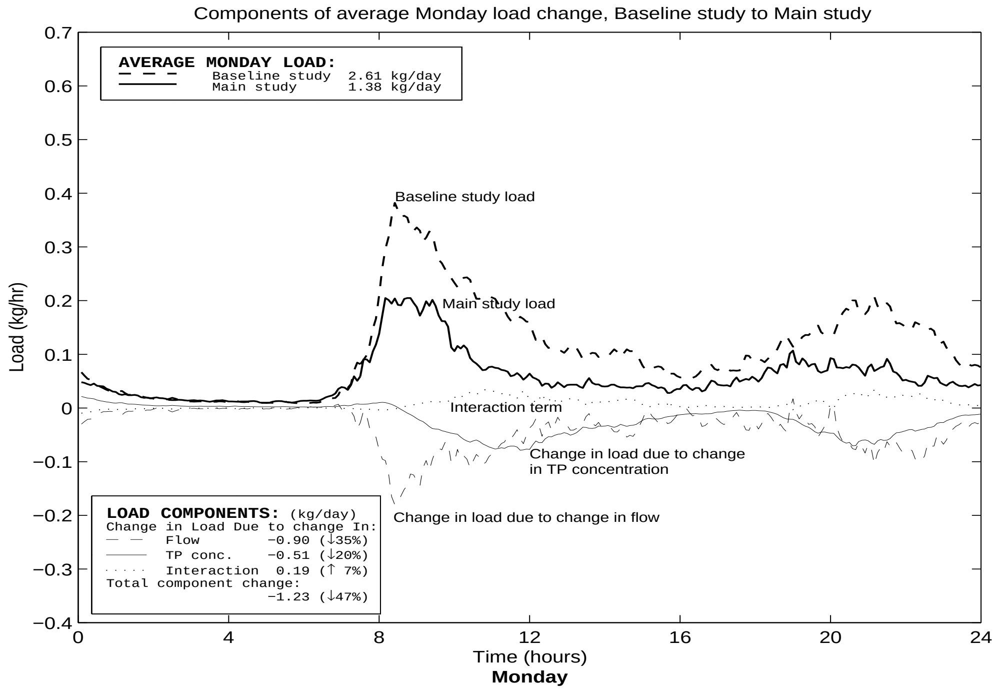

Figure 5.3: Components of daily load change for Monday, Baseline study to Main study

Tuesday

The Tuesday data, Figure 5.4, shows a reduction in load components that is highly correlated in the morning and less correlated in the evening where the change in load due to change in concentration, $f \cdot \delta c$, is small. In the morning there is a reduction in load with both components reducing significantly shortly before 8.00 a.m. and then peaking about 9.00 a.m. The second order interaction term shows a significant value at the same time. The reduction in load terms then fall off to an early afternoon low. The small contribution to load change from the $f \cdot \delta c$ term in the evening is consistent with what is seen on with Thursday, Saturday and Sunday. On these days the fall in phosphorus load is from the $\delta f \cdot c$ term rather than from the $f \cdot \delta c$ term.

It is hypothesised that either this is a relatively low laundry period with insufficient laundry being built up over only one day to warrant another wash, or that washing is able to be done during the day rather than in the evenings such as on weekend days. This two day cycle is supported by the social survey data (Table 3.15), which shows Tuesday and Thursday to be the least likely washing days, and Wednesday and Friday among the most likely. Saturday is the day when households are most likely to wash, however we can assume that this washing is done during the day and does therefore not show up as an evening signal, as with the Friday and Wednesday data. This would also be the case on Sundays. The alternation of evening characteristics and that of the heavy and light washing days are the likely causes of the cyclicity detected in the wavelet analysis (Figure 5.12). The coherence of these structures can be readily upset by rain and other events and small changes such as major sporting events.

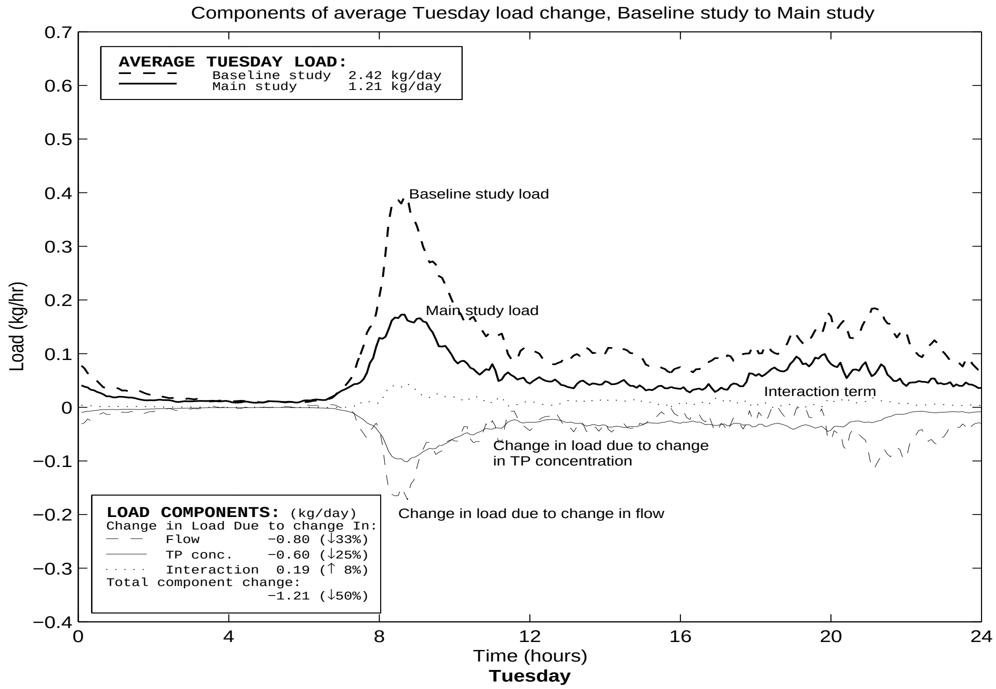

Figure 5.4: Components of average daily load change for Tuesday, Baseline study to Main study

Wednesday

The Wednesday data, Figure 5.5, closely resembles the Monday structure, especially in the afternoon where there is a significant reduction in load from both components and a noticeable positive interaction term.

The Wednesday pattern has very strong morning peaks and exhibits the greatest load reduction, 1.36 kg/day (51%) from the baseline study period compared with other days. Change due to the flow component is marginally positive, signifying an increased main study load, in a small period just before 8.00 a.m. However it quickly changes to the common negative value.

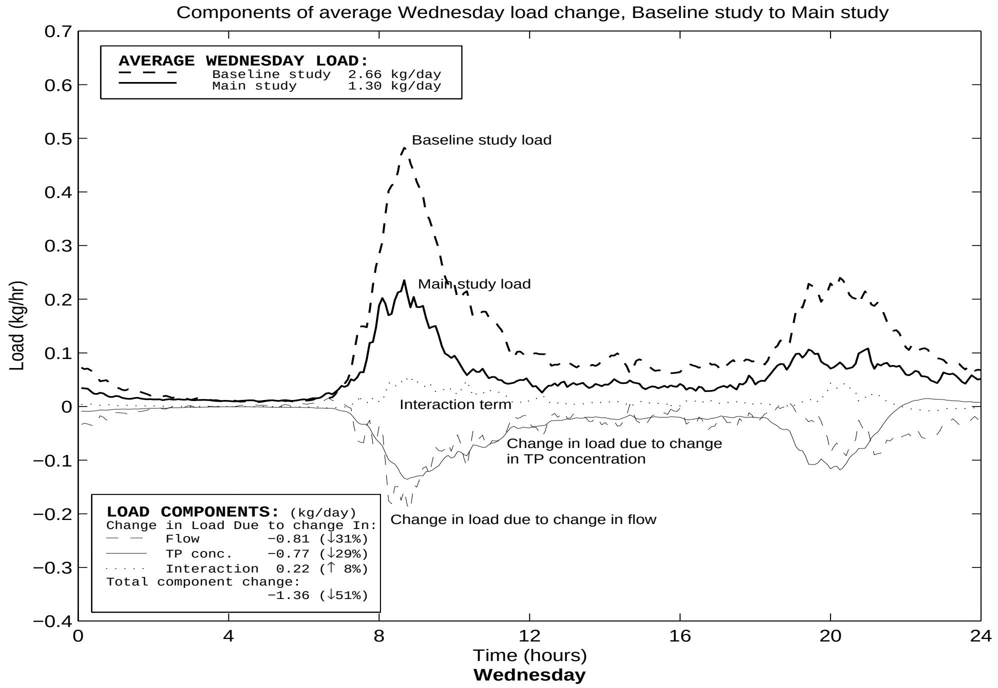

Figure 5.5: Components of average daily load change for Wednesday, Baseline study to Main study

Thursday

The Thursday data, Figure 5.6, shows similar patterns to Tuesday's data, as discussed previously, corresponding to low washing days identified in the social survey. A particular feature of Thursday is that it is the day where phosphorus load reaches its lowest absolute level. Compare, for example, the Monday loads of 2.61 kg/day and 1.38 kg/day for the baseline study and main study periods with 2.27 kg/day and 1.22 kg/day for the same periods on Thursday.

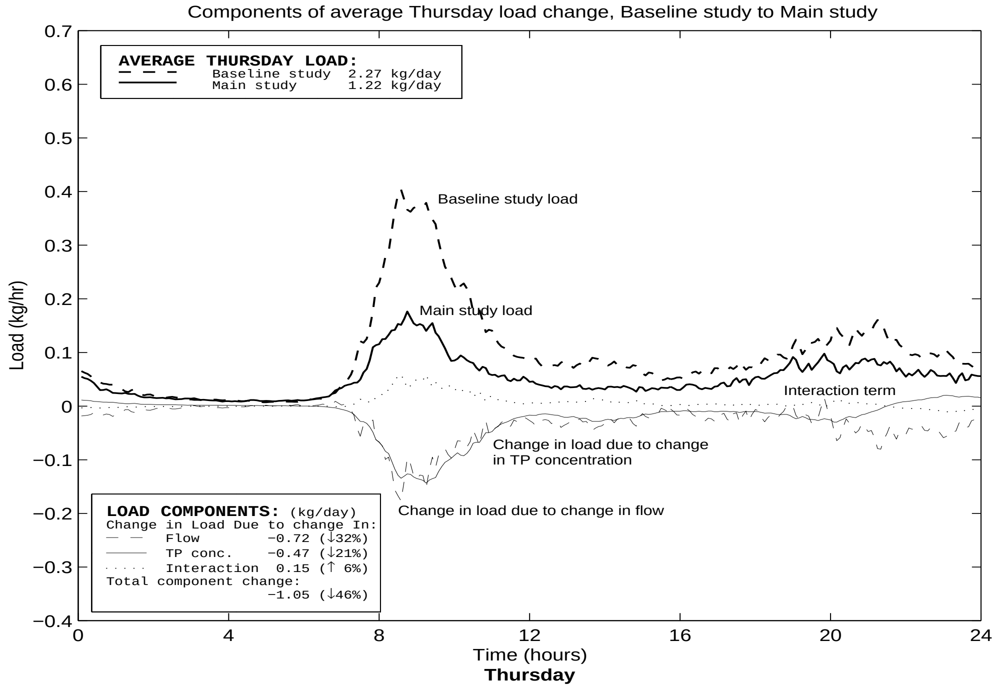

Figure 5.6: Components of average daily load change for Thursday, Baseline study to Main study

Friday

The Friday data, Figure 5.7, is unusual for its load reduction due to the reduction in flow, $\delta f \cdot c$. In this figure it is seen that the usual load reduction due to flow occurs around the morning peak of 8.00 a.m. but this quickly drops and even becomes a positive contribution to load around 10.00 a.m. This contrasts with the usual pattern of a slow decline in the magnitude of the $\delta f \cdot c$ term, settling to an afternoon trough of near zero contribution to load change around 1 p.m. There is also a small period near 7 p.m. when $\delta f \cdot c$ is positive and the interaction term is negative. On Friday then, there was little significant overall reduction in flow between 10.00 a.m. to 6.00 p.m. This flow characteristic also shows up in the tabulated data of Table 5.1 where Friday is the only day where load reduction due to changes in flow is lower than the reduction due to changes in concentration. This consistency in flow between the baseline and main study while concentration is reduced implies a period where *waterwise* practices are not being implemented and the only change in the system is due to the use of phosphorus-free detergent.

The separation between the baseline study and the main study loads in the mid afternoon period, when the reduction in load due to a reduction in flow is small, is minimal. Indeed near 7 p.m. the loads are similar. This feature is repeated in the two weekend figures, Saturday and Sunday. It is hypothesised that these periods correspond to activity that has not been targeted by this study. That is, there are periods where flow is not mitigated and there is only a small change in phosphorus usage primarily because laundry use is not the principal source.

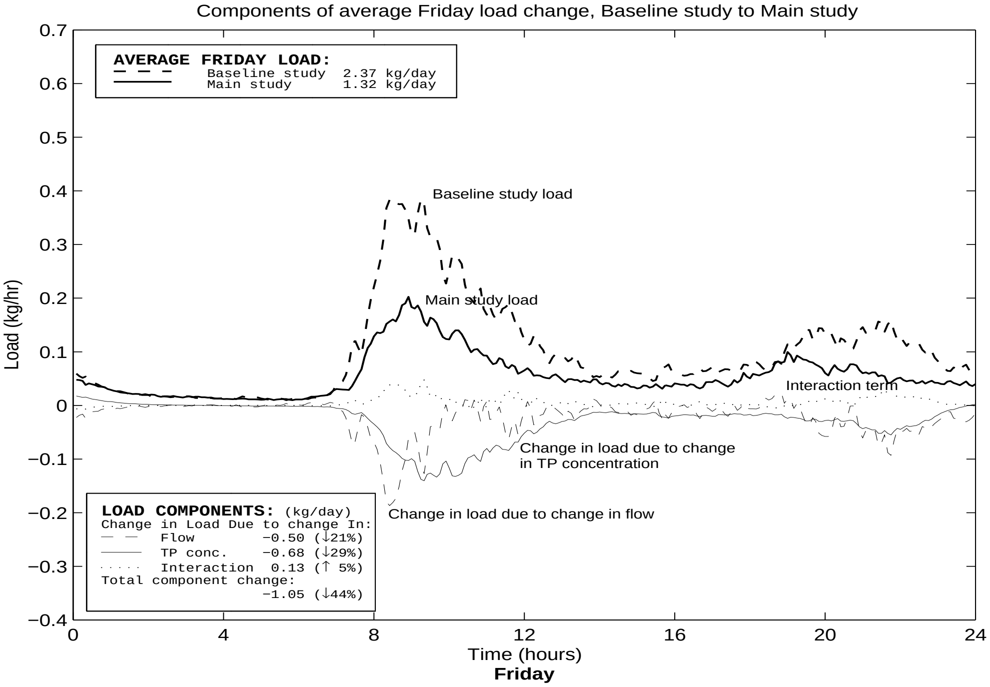

Figure 5.7: Components of average daily load change for Friday, Baseline study to Main study

Saturday

The Saturday data, Figure 5.8, shows quite different load patterns to the weekday figures. The principal difference is in the timing and rate of peak changes. In the weekday figures the leading edge of the morning peak is quite steep with the maximum being reached shortly after 9.00 a.m. On Saturday the rise in load is later and less steep. However the peak is much broader. It has a significant amplitude at 12.00 midday whereas the weekday curves have fallen to near their minimum values at this time. The evening peak occurs much earlier than on weekdays, around 6.00 p.m. and is relatively narrow.

The pattern of load reduction is also different to that of weekday figures. There is a major fall in the reduction due to phosphorus changes, $f \cdot \delta c$, near 9.30 a.m. This is accompanied by a fall in the reduction due to flow component which remains quite variable throughout the day. It is hypothesised that the variability and the resultant structure are primarily due to those community members who opted not to participate in study continuing to use their existing phosphorus based laundry products while simultaneously not adopting *waterwise* practices.

Saturday is the only day that does not have a clear peak reduction due to reduction in flow, $\delta f \cdot c$, in the evening, although the peak on Thursdays is fairly small. That is, *waterwise* practices do not appear to be as dominant in the evening as they are on weekdays. The reduction due to concentration, $f \cdot \delta c$, in the afternoon/evening is similar to the pattern seen on low wash days such as Tuesday and Thursday. There is a small, constant reduction in phosphorus concentration throughout the afternoon and evening, with a return to baseline conditions around 10.00 p.m. As Saturday is identified in the social survey as a high wash day, this implies that most washing is done in the morning.

The event near 7 p.m., where there is no net reduction in phosphorus load, is interesting. The reduction in load due to flow becomes positive, signifying an increase in load due to an increase in flow. It is seen from the reduction in load due to phosphorus concentration that concentration changes are small and hence load changes are dominated by changes in flow. As discussed in the section on Friday's load pattern this indicates a significant activity that is not connected with laundry activity. We are not able to hypothesise or state whether the activity is more dominant on one day in the study period than another, and hence is an anomalous situation.

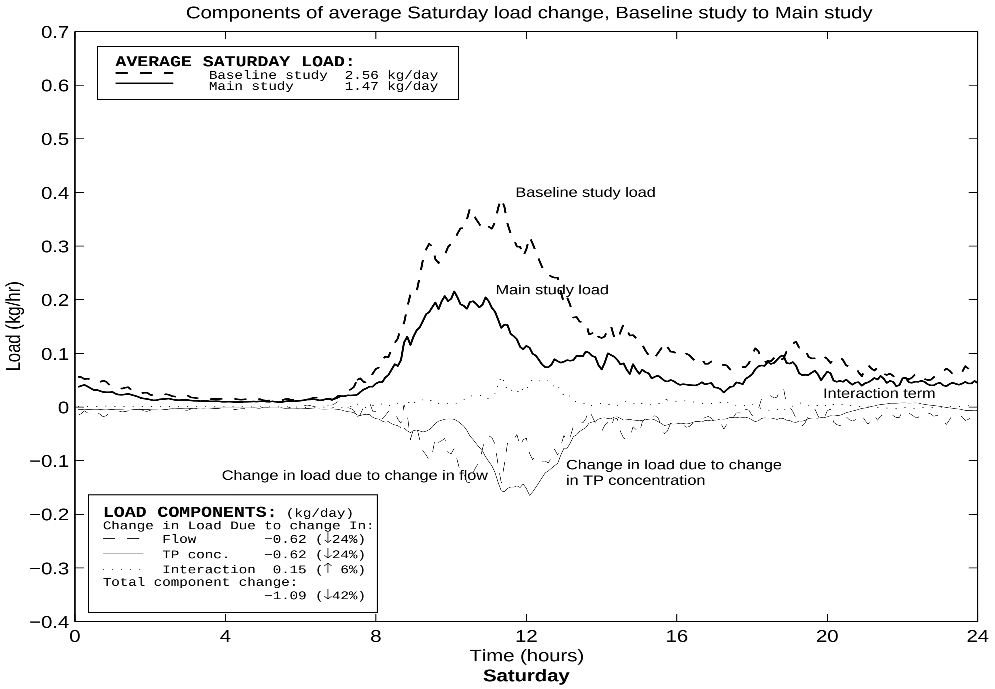

Figure 5.8: Components of average daily load change for Saturday, Baseline study to Main study

Sunday

The Sunday data, figure 5.9, is more like the weekday figures than the Saturday figure, except that the onset of the morning peak is significantly after 8.00 a.m. Sunday shows the highest levels of correlation between the various signals. This is readily seen in the second order interaction term which is 0.24 kg/day for Sunday compared with, for example, 0.19 kg/day for Monday (Table 5.1).

Other features of Sunday's phosphorus load include:

- A period between 6.00 a.m. and 9.00 a.m. when the reduction due to flow is marginally positive. The behaviour here is similar to Saturday.
- The late evening reduction peak characteristic of Monday, Wednesday and Friday conditions is present, however unlike these other days the change is due mostly to changes in flow.

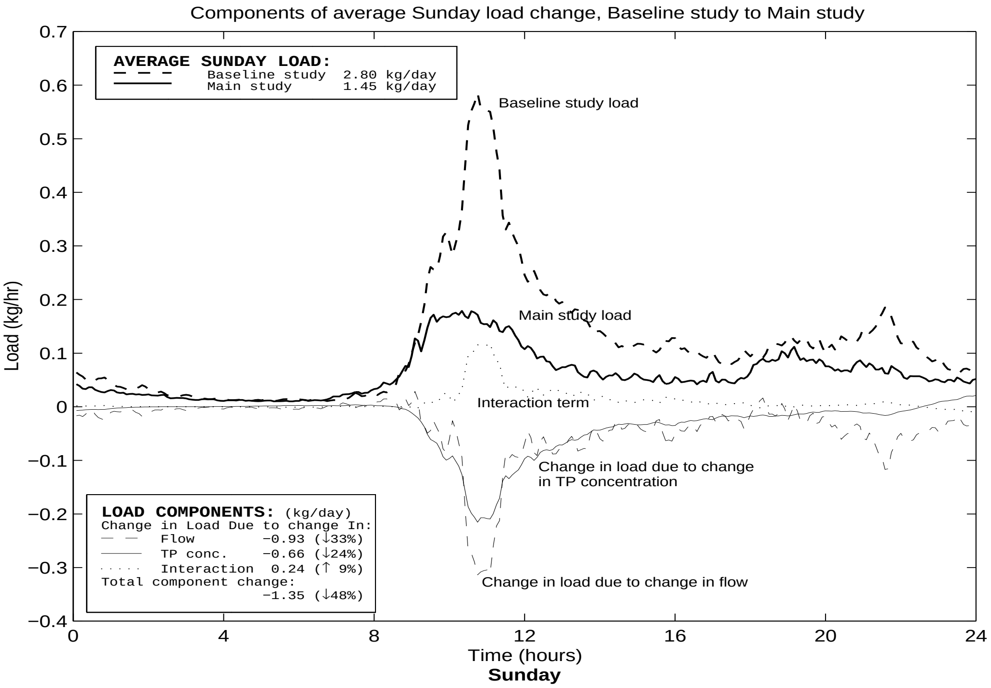

Figure 5.9: Components of average daily load change for Sunday, Baseline study to Main study

5.1.3 Frequency domain results

It is important to understand that time domain and frequency domain analysis are complementary techniques. Additional information, not available in one domain, may be extracted from the other domain.

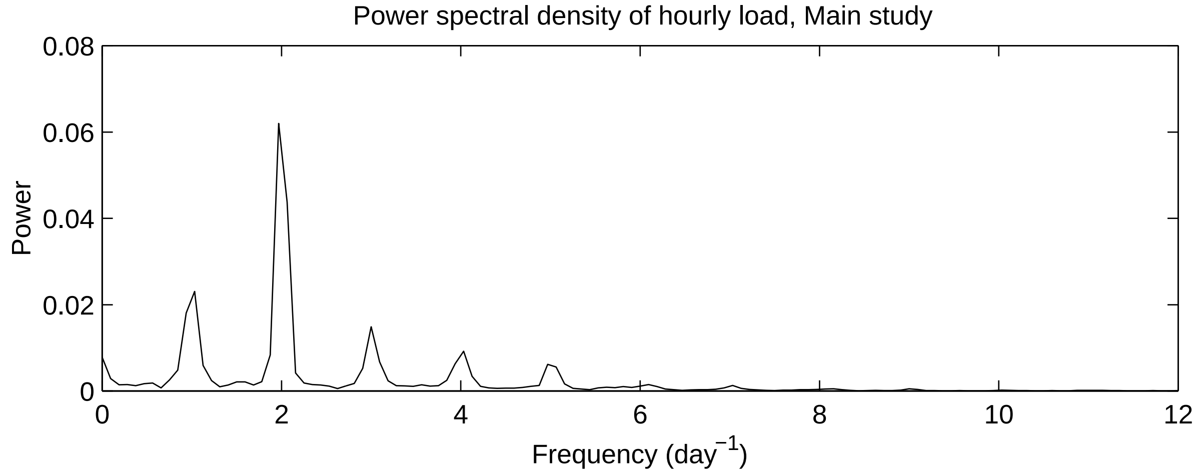

Figure 5.10: Power spectral density of load, Main study

Power spectral density plots using the Welch algorithm as implemented in Matlab's Signal Processing Toolbox (MathWorks 1996a) were performed on all data sets to identify the dominant frequency components. A typical power density plot is shown in Figure 5.10. The plot shows a sequence of peaks whose frequencies are 1.00, 2.00 3.00 and 4.00 cycles per day with the first two frequencies dominating. The amplitude and phase of these dominant frequencies are tabulated in Table 5.2. It is seen from both the figure and the table that it is the semi-diurnal component that is dominant. Figure 5.11 is a partial reconstruction of the main study period load using the two dominant frequencies and the mean offset. The basic structure of an elevated, more intense, morning peak and a less dominant evening peak result from the addition of these signals, indicating that the classical $\mathcal{W}$ daily load pattern is the sum of two individual components. The addition of other components is required to achieve full reconstruction.

The study of the individual flow and concentration components of load is less clear. Table 5.2 shows that there is consistency in the spectral content of the load and flow signals between the baseline study and the main study periods but the spectral content of phosphorus concentration changes. This is not too surprising as the introduction of phosphorus-free laundry detergents would modify phosphorus concentration patterns. It is noted, however, that flow was primarily modified in amplitude, equivalent to changing average volume, rather than by changing the frequency content of the signal. This is consistent with the adoption of *waterwise* practices.

In much the same way that the time series analysis moved from average results into more detailed and specific daily analysis to bring out differences between the days, conventional frequency analysis makes way for time varying wavelet analysis. Wavelet decomposition was performed on the both the baseline and main study data sets. However it is not practical to compare the outcomes due to the limited amount of data in the baseline set and the natural variations that it contains. Figure 5.12 is a typical output obtained with the Matlab Wavelet Toolbox (MathWorks 1996b) using the orthogonal Daubechies *db*9 wavelet on hourly loads

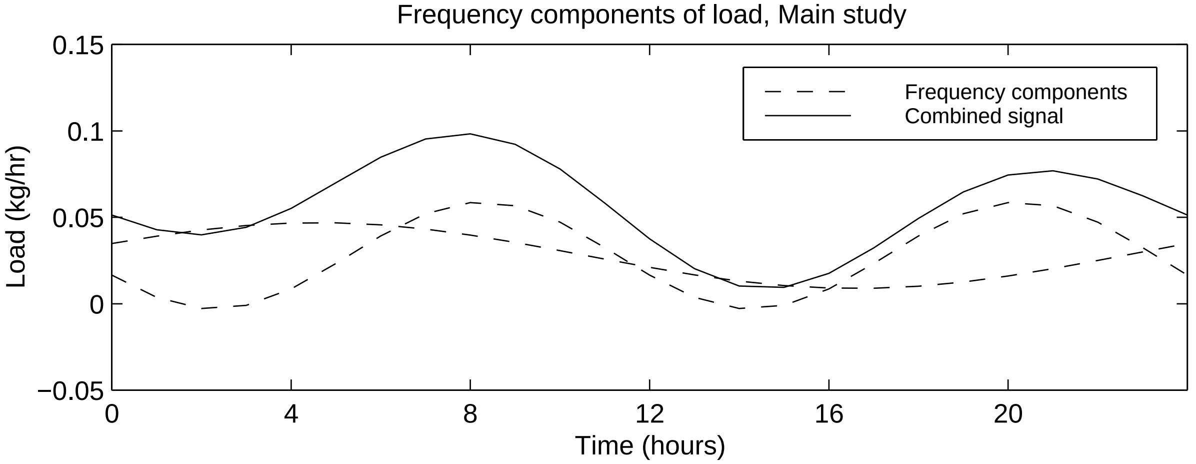

Figure 5.11: Frequency components of load, Main study.

Table 5.2: Significant spectral periods in load, flow and concentration

Study period	Load		Flow		Concentration	
Frequency (cycles/day)	Amplitude (kg/hr)	Phase (degrees)	Amplitude (ML/hr)	Phase (degrees)	Amplitude (kg/L)	Phase (degrees)
Baseline study						
1.0	0.041	178	0.0033	162	1.09	-144
2.0	0.058	83	0.0057	79	-	-
Main study						
1.0	0.019	176	0.0028	162	1.40	-60
2.0	0.031	91	0.0035	85	0.68	169

from the main study period. The level of the decomposition is mainly controlled by the length of the data set and the information that it contains. In the case of Figure 5.12 the data in the approximation panel, A7, is fairly flat, indicating that decomposition has reached a near constant DC level. That is, the signal has been satisfactorily decomposed.

The details panels of Figure 5.12, D1 to D7, show the high frequency signal at each stage of the decomposition. Panel D1, particularly between epochs 600 and 800, shows a high frequency signal repeating on a daily basis. Panels D2 and D3 show the details component of the signal as more of the higher frequency signal is accounted for. Panel D4 displays the details signal which is now represented by a relatively clean, daily (24 hour) signal. This signal is particularly clean and uniform between epochs 200 and 800, a period more than three weeks, however there are clear transitions around epochs 175 and 850. It is also to be noted that there is a scale between Panels D3, D4 and D5. This is in line with the above discussion which indicated that the amplitude of the semi-diurnal signal, contained in Panel D3, is larger than diurnal signal of Panel D4. Panel D5, particularly between epochs 200 and 600, shows a clear two day signal which supports the time domain discussion for Tuesday and other similar profile low laundry washing days as presented in the daily results section (Section 5.1.2).

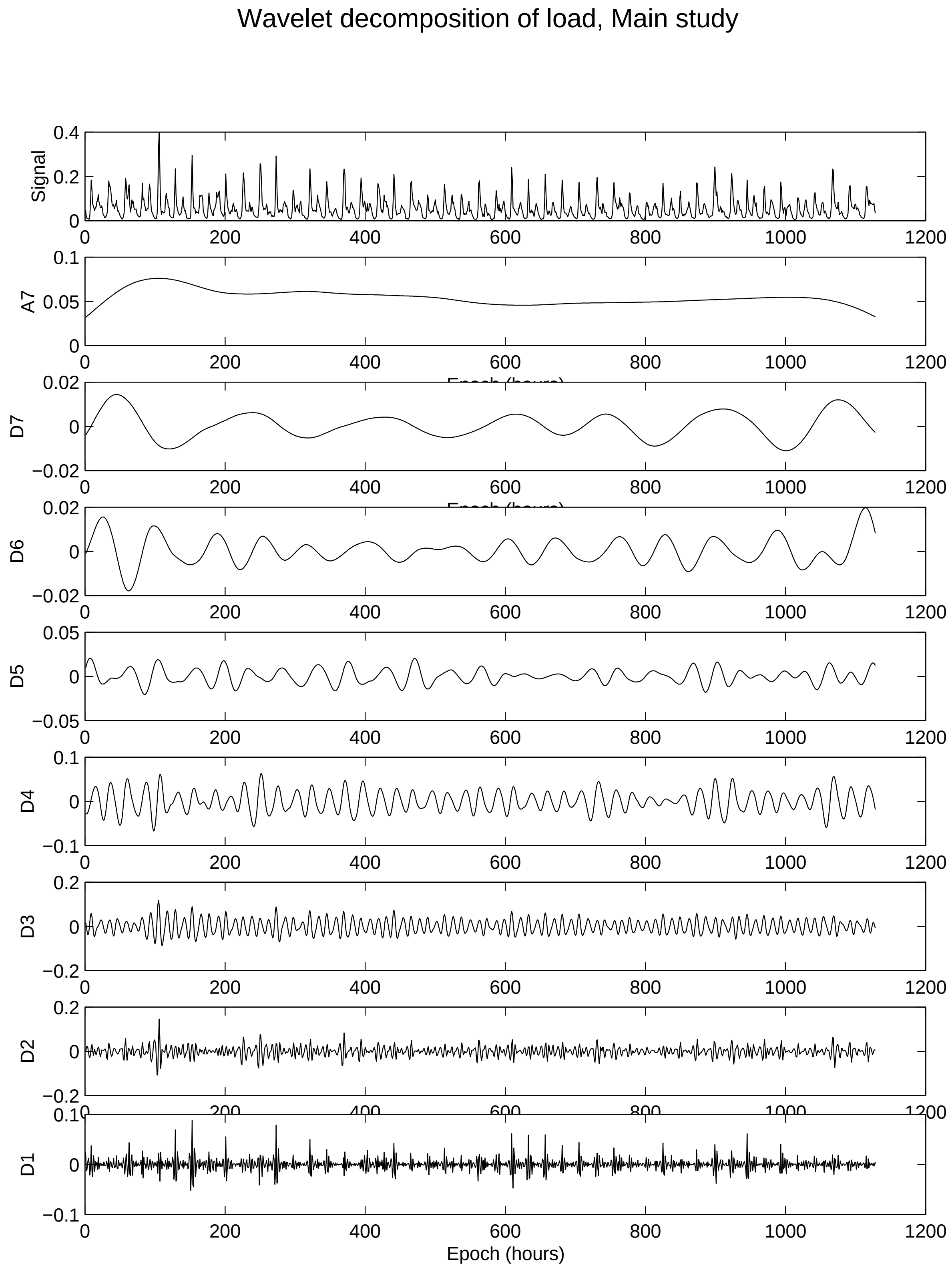

Figure 5.12: Wavelet decomposition of load, Main study

The information in Panels D6 and D7 is derived from much lower amplitude signals than the component present in Panel D5. The amplitudes are about half those of Panel D5 and hence individual contributions to the total power are a quarter. The period of the signal in Panel D6 is neither well defined nor stable. The variations in amplitude almost certainly result from a mixing of this signal with another low frequency signal whose period has not been fully sampled. This is in contrast to Panel D7 which exhibits a rather well behaved and stable weekly characteristic, 168 epochs, which is known to be present in the data due to the weekly cyclicity of laundry and water usage patterns.

5.2 Follow-up study

The multi-part time series approach used on the main study data set was also used on the shorter follow-up study data set. Thus the same five trace figures for baseline and follow-up data are generated and displayed as in Section 5.1, save that the main study is replaced by the follow-up study.

The follow-up study results are given in Figure 5.13. This figure shows the phosphorus usage of the Thurgoona community eight weeks after the phosphorus-free detergent trial ceased. The change in phosphorus load from the determined baseline value of 2.51 kg/day to a follow-up period value of 2.58 kg/day, a change of 3%, is not considered significant. This value includes both the component due to flow and the component due to concentration and so represents the upper limit. The lower limit, the load change that is due only to concentration, is a reduction of -0.26 kg/day or 10%. The phosphorus concentration levels remained depressed relative to the baseline study indicating that a proportion, 43%, of trial participants have continued to use phosphorus-free detergents.

The two most striking features of Figure 5.13 are the similarity between the baseline load with the follow-up load and the repartitioning of the load as indicated by the components $f \cdot \delta c$ and $\delta f \cdot c$ and the interaction term. The figure shows that the change in flow component dominates the change in concentration component. Section 3.1.2 discusses the problems that were experienced in reducing the data set in this study period and the uncertainties associated with replacing the logger and calibrating the new logger to a constant community usage. These problems suggest that significant flow biases remain in all three data sets and that the increase in flow seen here is as probable as the decrease discussed in the results associated with the main study period.

Figure 5.13 shows that changes due to the phosphorus concentration are limited to around 8.00 a.m. when most laundry activity takes place. Thereafter there is little change and hence the interaction term is zero. This strengthens the hypothesis that a proportion of the community found phosphorus-free laundry detergents satisfactory for their laundry needs and hence did not revert to phosphorus based products after the main study. The component due to flow is strongly positive in the 8.00 a.m. to 10.00 a.m. and 6.00 p.m. to 8.00 p.m. periods with a minimum, near zero, between 10.00 a.m. and 4.00 p.m. The magnitude of the component due to flow is similar to that shown in Figure 5.1. In this figure the component due to flow peaks shortly after 8.00 a.m. at -0.12 kg/hr and then just after 9.00 p.m. at -0.05 kg/hr. This is to be compared with positive peaks of 0.13 kg/hr shortly after 8.00 a.m. and 0.8 kg.hr just before 8.00 p.m. This suggests that variations in flow, probably constant bias levels, still exist in the flow data and thus care must be made in interpreting the results.

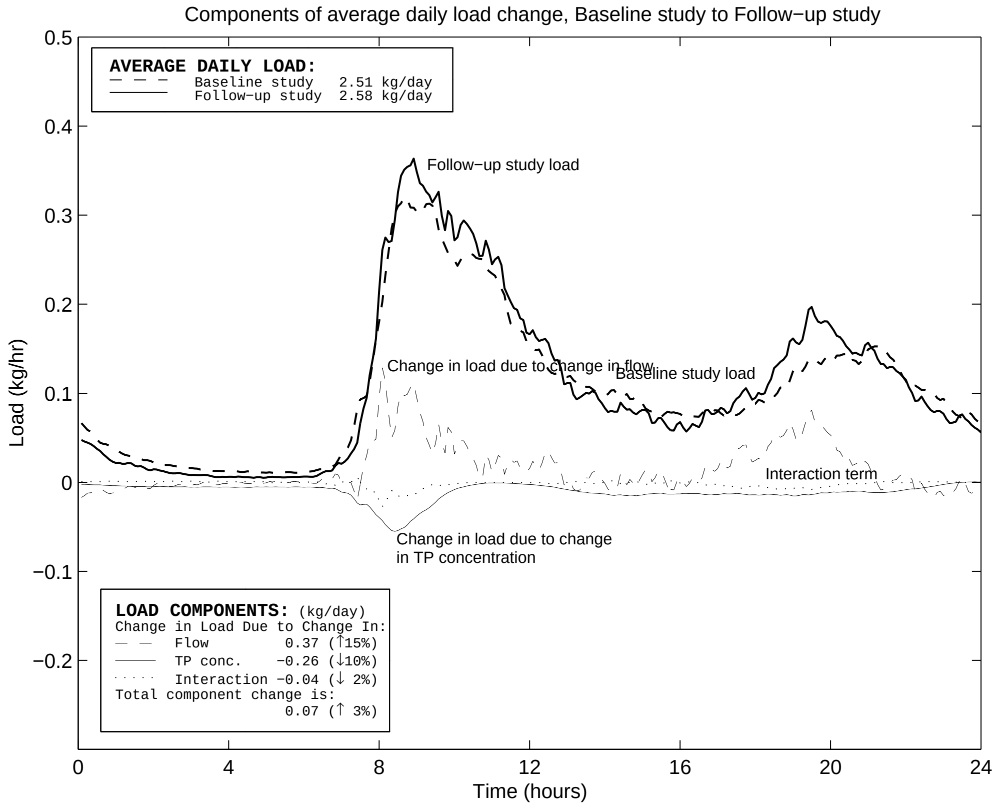

Figure 5.13: Components of average daily load change from Baseline study to Follow-up study

Frequency analysis of the follow-up data set was undertaken to determine the dominant frequencies and their magnitude and phase. The results are shown in Table 5.3. A comparison with the baseline study and main study data (see table 5.2) indicates that it is diurnal component that contributes to the change, with the amplitude of the flow signal increasing from 0.0033 ML/hr in the baseline study to 0.0049 ML/hr in the follow-up study. The phase relationship remain constant. The spectral content for the phosphorus concentration again shows variability with a significant unexplained peak at three cycles per day.

Table 5.3: Significant spectral periods in load, flow and concentration, Follow-up study

Study period	Load		Flow		Concentration	
Frequency (cycles/day)	Amplitude (kg/hr)	Phase (degrees)	Amplitude (ML/hr)	Phase (degrees)	Amplitude (kg/L)	Phase (degrees)
Follow-up study						
1.0	0.052	176	0.0049	162	1.04	168
2.0	0.062	87	0.0058	90	1.46	72
3.0					0.74	-22

There was insufficient data to perform a reliable wavelet decomposition of the follow-up data set.

Chapter 6

Conclusions

This study, *The Effect on Sewage Phosphorus Loads Using Phosphorus-free Laundry Detergent*, has determined the contribution that laundry detergent phosphorus makes to wastewater phosphorus load, both in the long term and on a daily level, and determined the medium term level of community acceptance of phosphorus-free detergents.

The change in phosphorus load from baseline levels has been partitioned into change due to flow, $\delta f \cdot c$ and change due to phosphorus concentration, $f \cdot \delta c$. The overall change in load from the baseline study to the main study, the period of phosphorus-free detergent usage, was a reduction of 47%. This total change represents an upper limit of the reduction as it includes reductions due to changes in flow, which may be due to the community adopting *waterwise* practices, and those changes that are due to changes in phosphorus concentration alone. This latter change, a reduction of 24%, represents a lower limit on the effect of introducing phosphorus-free laundry detergent. It represents changes due only to phosphorus concentration and therefore accommodates the possibility that the changes seen in flow were not indicative of what was occurring in the community.

These results were obtained with a community participation rate of 64%, 25% of whom were already using phosphorus-free detergent. Results were not adjusted for the participation factor as there will always be members of the community who will prefer to use phosphorus detergents.

For the study community, the reduction was from a baseline load of 2.5 kg/day to 1.3 kg/day. Assuming similar participation levels and a dominantly domestic source it is anticipated that, on a city wide basis, the average daily load of phosphorus discharged to the treatment works could fall from the current level of 120 kg/day to around 65 kg/day, although in reality this latter figure would be elevated by some industry contribution.

Reductions of this magnitude have the potential for significant cost savings in the operation of a wastewater treatment plant as the plant will operate at a higher level of efficiency and will use lower levels of dosing chemicals which in turn will lower the risk of land degradation due to salinisation.

The splitting of the load reduction into the components due to changes in flow and concentration has allowed several results to extracted. These results are seen in both the time series analysis and the frequency analysis. The more important results are:

- Laundry characteristics vary between each day of the week.
- There is an underlying two day cycle of laundry activity with more washing being done on Monday, Wednesday and Friday than on Tuesday and Thursday. This is supported by the social survey data.
- On the week days where more washing is done, Monday, Wednesday and Friday, load patterns show evidence of washing in both the morning and the evening.
- Saturday is the day that has the greatest amount of washing, shown by the social survey. The similarity of evening load patterns with that of low wash days, Tuesday and Thursday, indicate that washing is done during the day on Saturday.
- The load pattern seen on days such as Saturday indicates that a portion of the community were not using phosphorus-free products. This is in line with the 36% of the community that declined to participate in the study.
- The load can be represented by a number of signals of which the two most important are the diurnal and semi-diurnal signals. The addition of these two signal accounts for the principal two peak structure that is evident in daily load. There is a strong suggestion that the semi-diurnal signal is more closely allied to laundry habits than the diurnal signal.

The follow-up campaign was important for overall validation as well as to determine possible long term changes in the community's laundry habits. Using the total change, the sum of changes due to both flow and concentration, it is seen that there is a small, 3%, change in load from the baseline period to the follow-up period, a span of six months. This change is an upper estimate and is not considered significant due to the small amount of quality data that was available in the follow-up period.

The change due solely to changes in phosphorus concentration, the lower limit of change, was a reduction of 10% or 0.26 kg/day relative to the baseline study. That is, the contribution of phosphorus concentration to load was less in the follow-up study period, representing a medium term change in the community's habits. The return of the flow to levels exceeding the baseline period is of concern. Either the flow is poorly known, even after extensive post processing, or is highly influenced by the adoption and discontinuation of *waterwise* habits.

The most troublesome parameter in the calculation of load is the flow. In this series of trials, flow data required extensive post processing to ensure that it was free of the trends and biases resulting from the observation and reduction methods. After this post processing, changes due to flow dominate those due to phosphorus concentration indicating the importance of the flow parameter. By splitting the total change into the component due to flow and the component due to concentration further mitigation of possible errors in flow is achieved as the reductions are more conservative.

Determining phosphorus concentration was less prone to difficulties and therefore resulted in more precise measurements than were achieved for flow. The adoption of a bulking strategy with 12 bulked 120 minute samples per day provided sufficient information for this study. There is little or no signal with a periodicity more frequent than six times per day which is the Nyquist period if no deconvolution is undertaken. This can be applied to other studies where high frequency data, periods of down to three of four hours, are required.

Chapter 7

Recommendations

This study highlights the contribution that laundry detergents make to the absolute level of phosphorus in sewage. The study also details areas where our knowledge and understanding of the sewerage system is poor. Thus the first set of recommendations is aimed at improving our knowledge of the system as a whole.

- A better understanding of the flow and its determination, using multiple instruments and different setups, is required. We recommend the calibration, preferably under controlled laboratory conditions, of all flow meters and a comprehensive determination of effects such as temperature, voltage and installation with the view of reducing uncertainty associated with the measurement of flow.
- It would be desirable to acquire a long term set of social and environmental data. A study of the natural variation in load could then be conducted and these variations identified using techniques such as wavelet analysis.
- A theoretical and observational study on the bulking strategy used for acquiring chemistry data, with a focus on sampling frequency, is recommended. It appears possible that the sampling frequency used can be further reduced, resulting in cost and time savings by reducing the number and frequency of trips to the sampling site, and reducing the number of samples to be analysed. A reduction in the number of samples would also end the need to use multiple laboratories for chemistry analysis.

The next recommendations are associated with extending our knowledge of phosphorus in sewage and in sewage treatment plants. In particular it is desirable to know how the results from this study scale to the community as a whole and to be able to quantify the advantages of reducing phosphorus in wastewater.

- The collection of influent data on a city wide basis will allow tests for scalability. This requires some individual points containing a high proportion of industrial influent to also be monitored.
- Determining the average residence time for phosphorus and other particles in a biological nutrient plant.

- Determining the level of phosphorus that leaves the nutrient removal tanks as dissolved phosphorus.
- Determining the current level of phosphorus and other nutrients and salts in the effluent that leaves the treatment plant.

These tasks represent major commitments with a heavy outlay of resources. Despite this, there are considerable gains to be made in understanding the total sewerage system and its underlying processes which will permit the system to be described and modelled.

Chapter 8

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Appendix A

Albury/Thurgoona region

Dummy one page figure

Figure A.1: The Albury area

Dummy one page figure

Figure A.2: The Thurgoona Catchment Area

Appendix B

Load, flow, rainfall and phosphorus concentration: figures

This section contains a multipanel sequence of figures showing load, flow, rainfall and phosphorus concentration on the same page. The figures are organised by time, with the baseline study presented first, and the follow-up study last.

The flow and concentration data presented has a five minute sampling period, while the period of the load is hourly, and the rainfall daily. The rainfall levels come from the rain gauge at Corry's Wood.

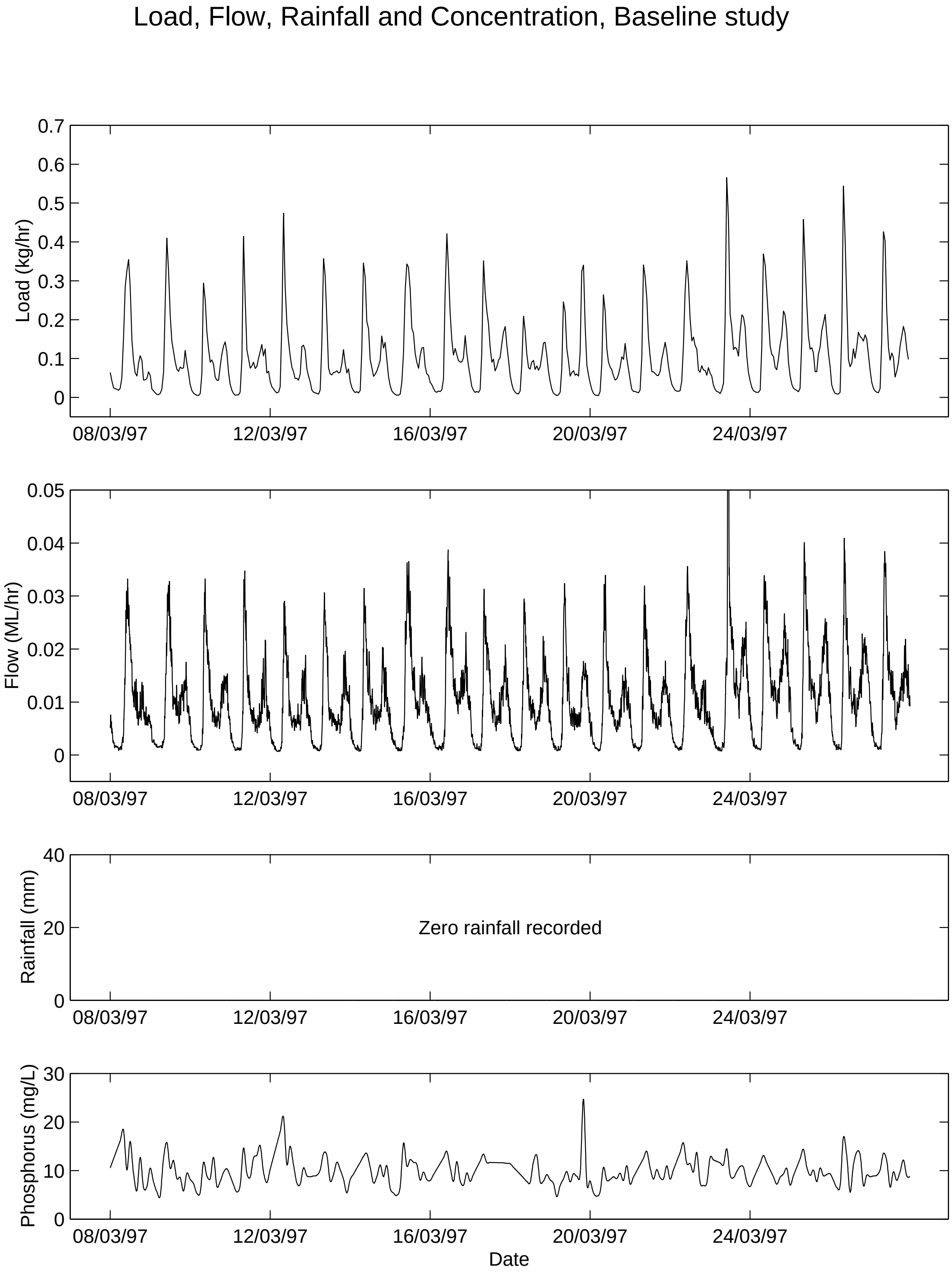

Figure B.1: Load, flow, rainfall and TP concentration, Baseline study

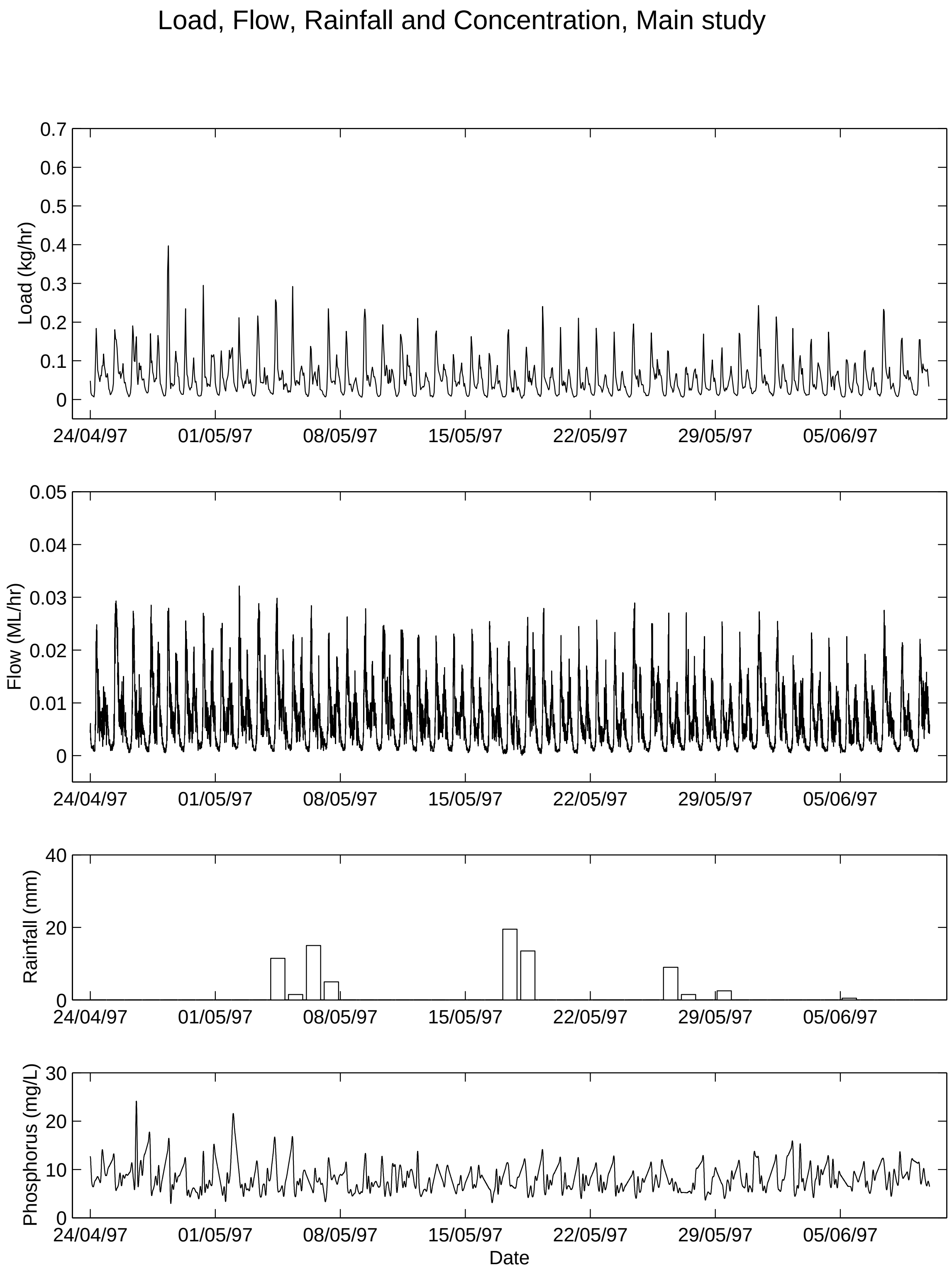

Figure B.2: Load, flow, rainfall and TP concentration, Main study

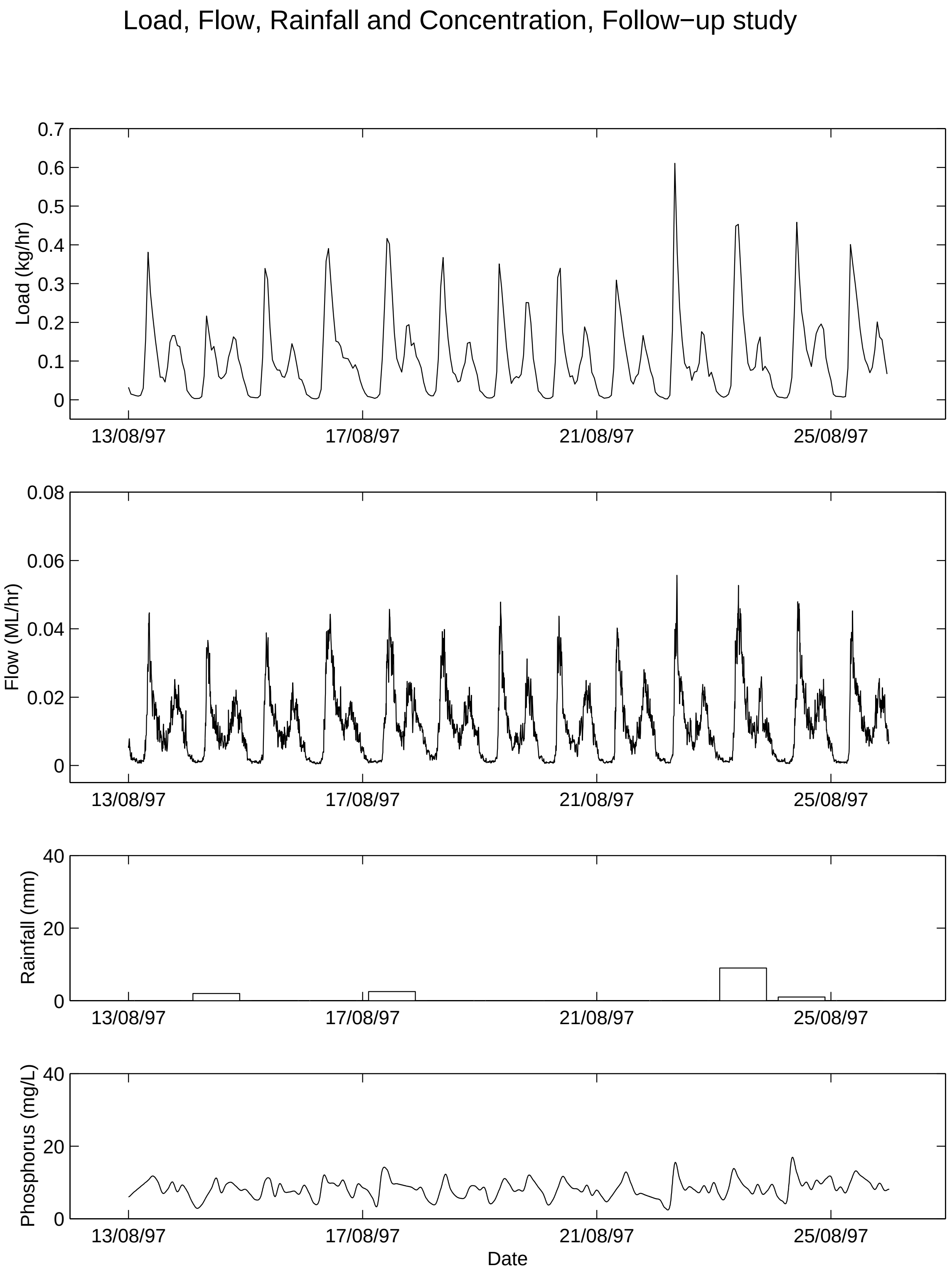

Figure B.3: Load, flow, rainfall and TP concentration, Follow-up study

Appendix C

Average load, flow and concentration per day of week: figures

This section contains multipanel figures showing the average load, flow and concentration for each day of the week. The figures are organised by time, with the baseline study presented first and the main study last. The follow-up study does not provide enough data to present this information, due to its short duration.

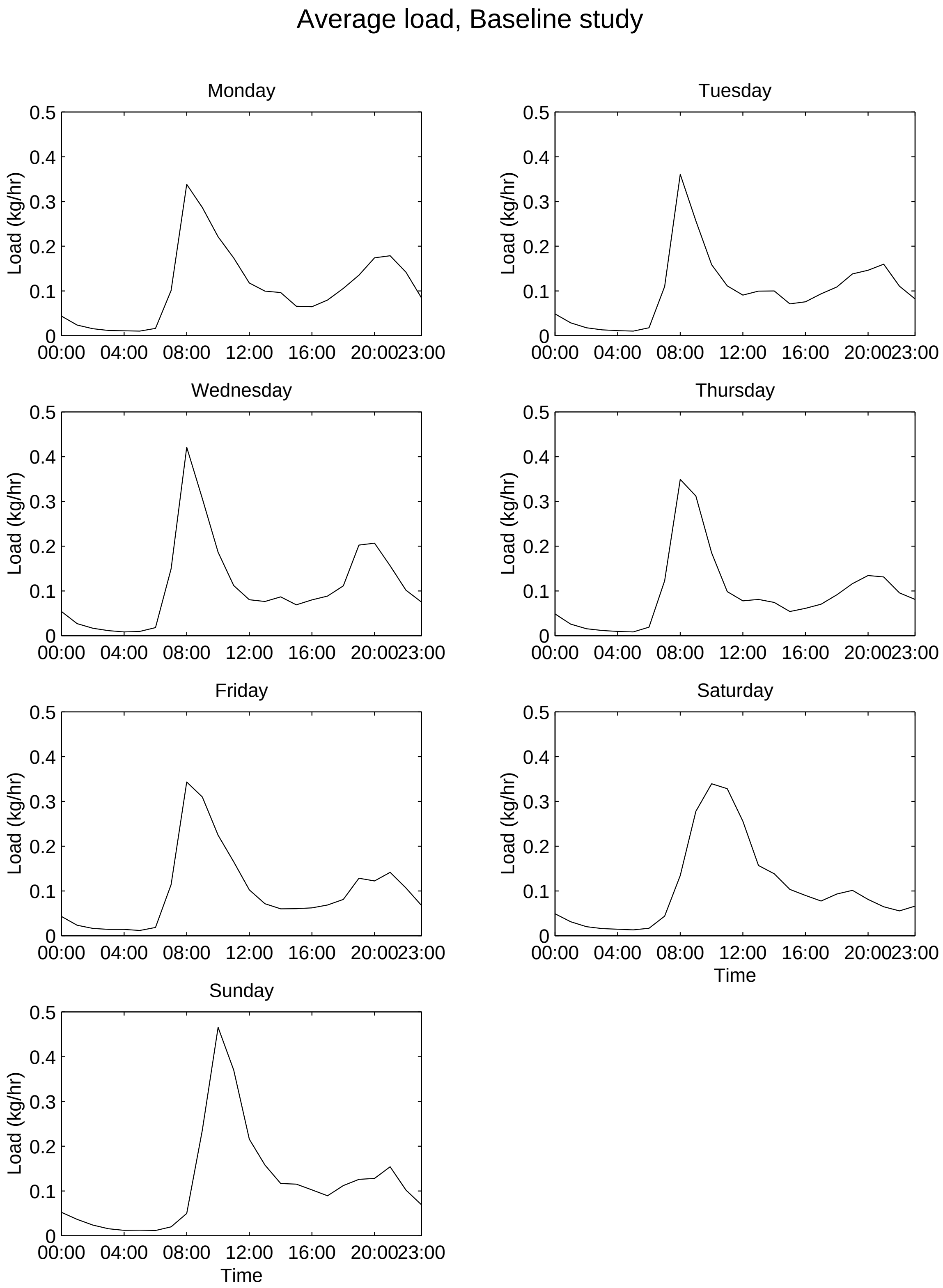

Figure C.1: Average load per day of week, Baseline study

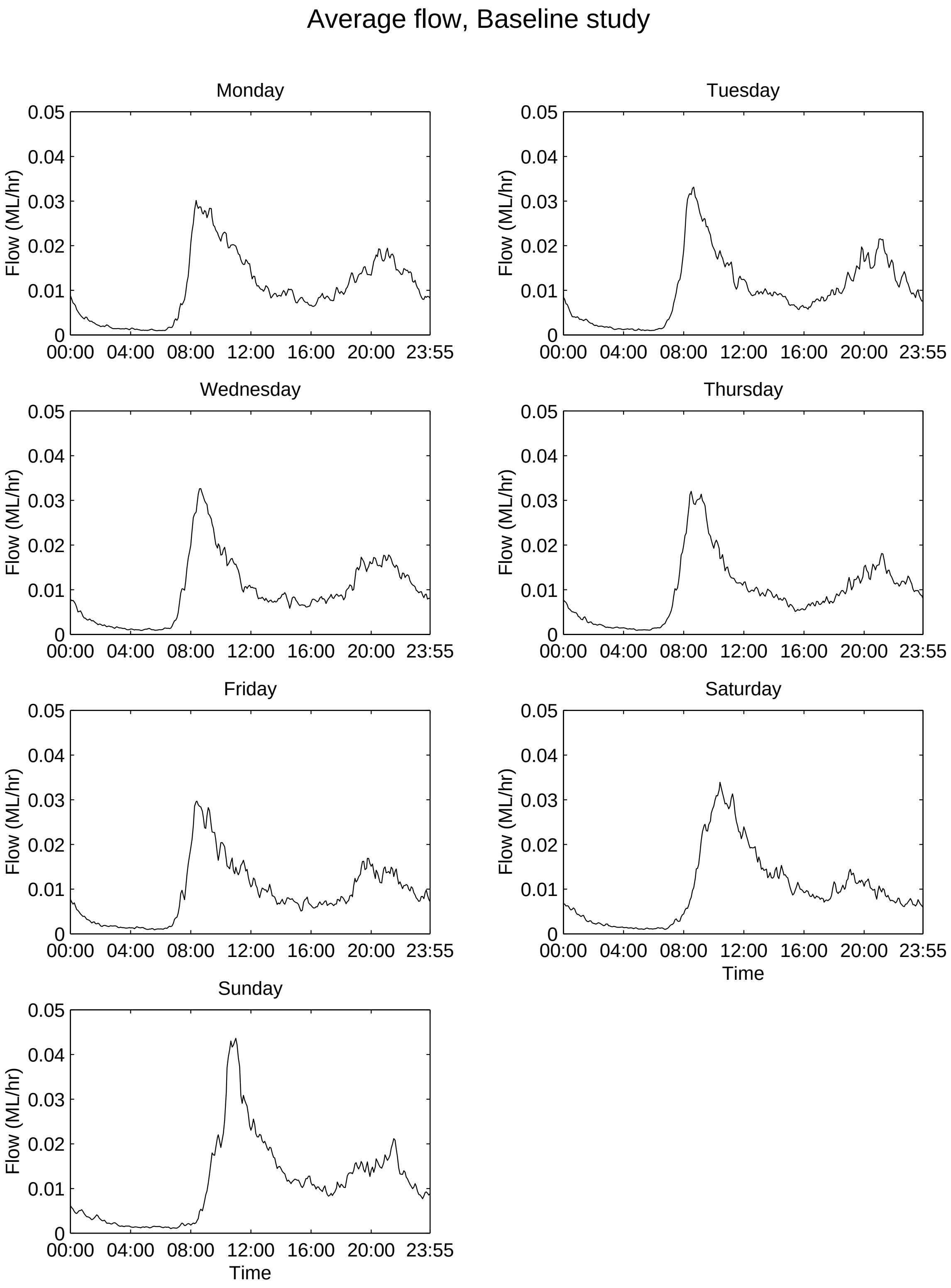

Figure C.2: Average flow per day of week, Baseline study

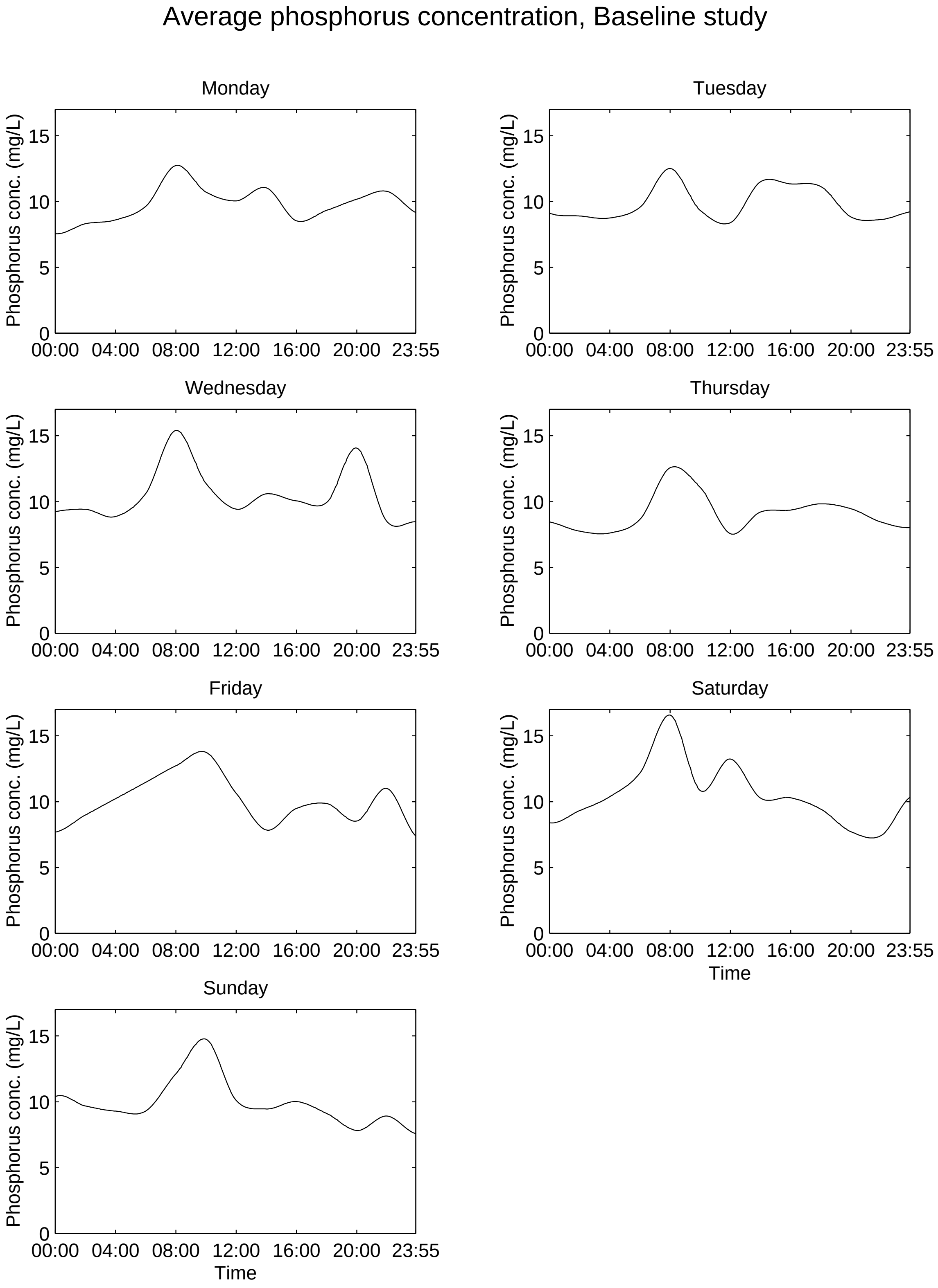

Figure C.3: Average phosphorus concentration per day of week, Baseline study

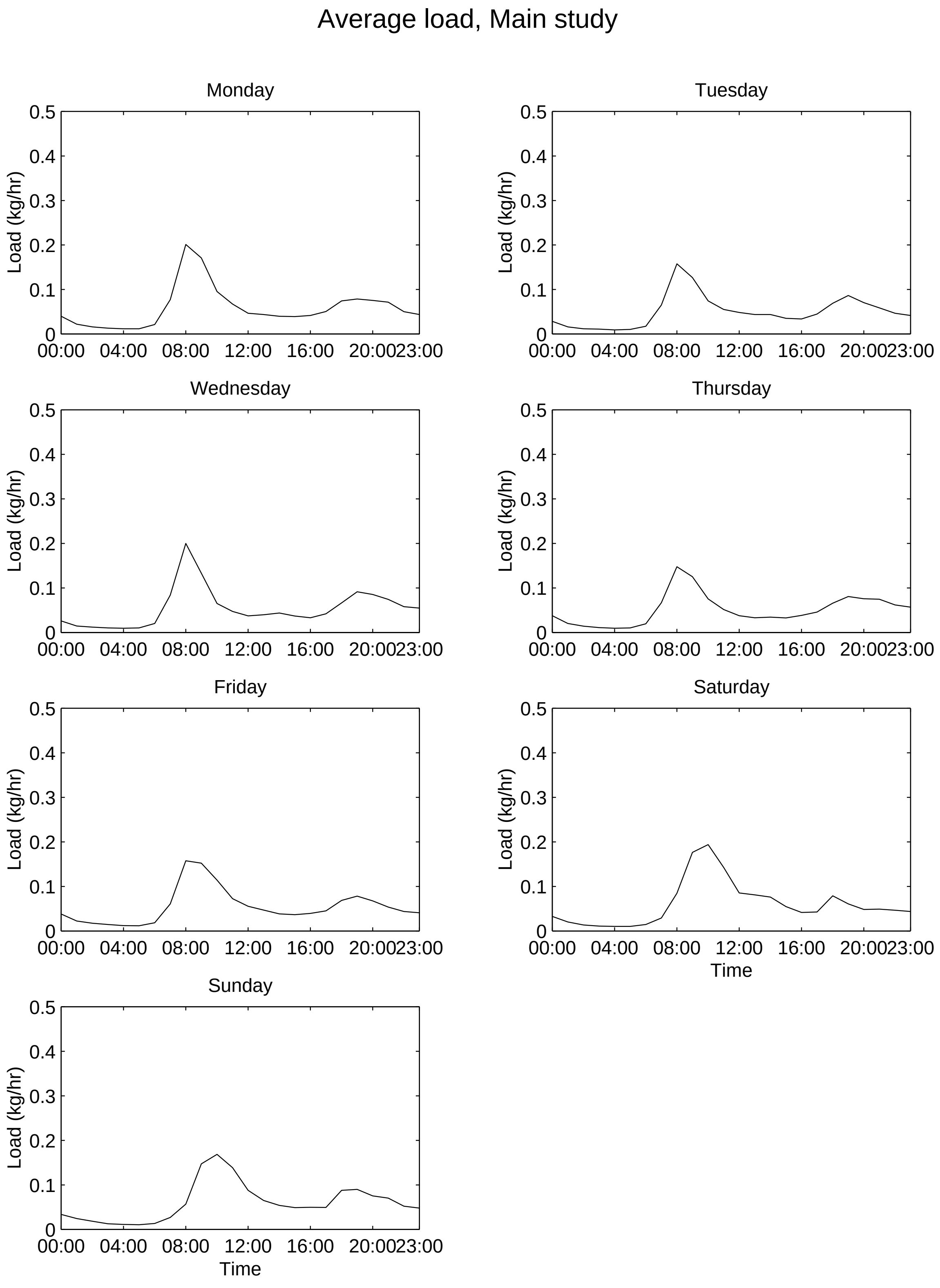

Figure C.4: Average load per day of week, Main study

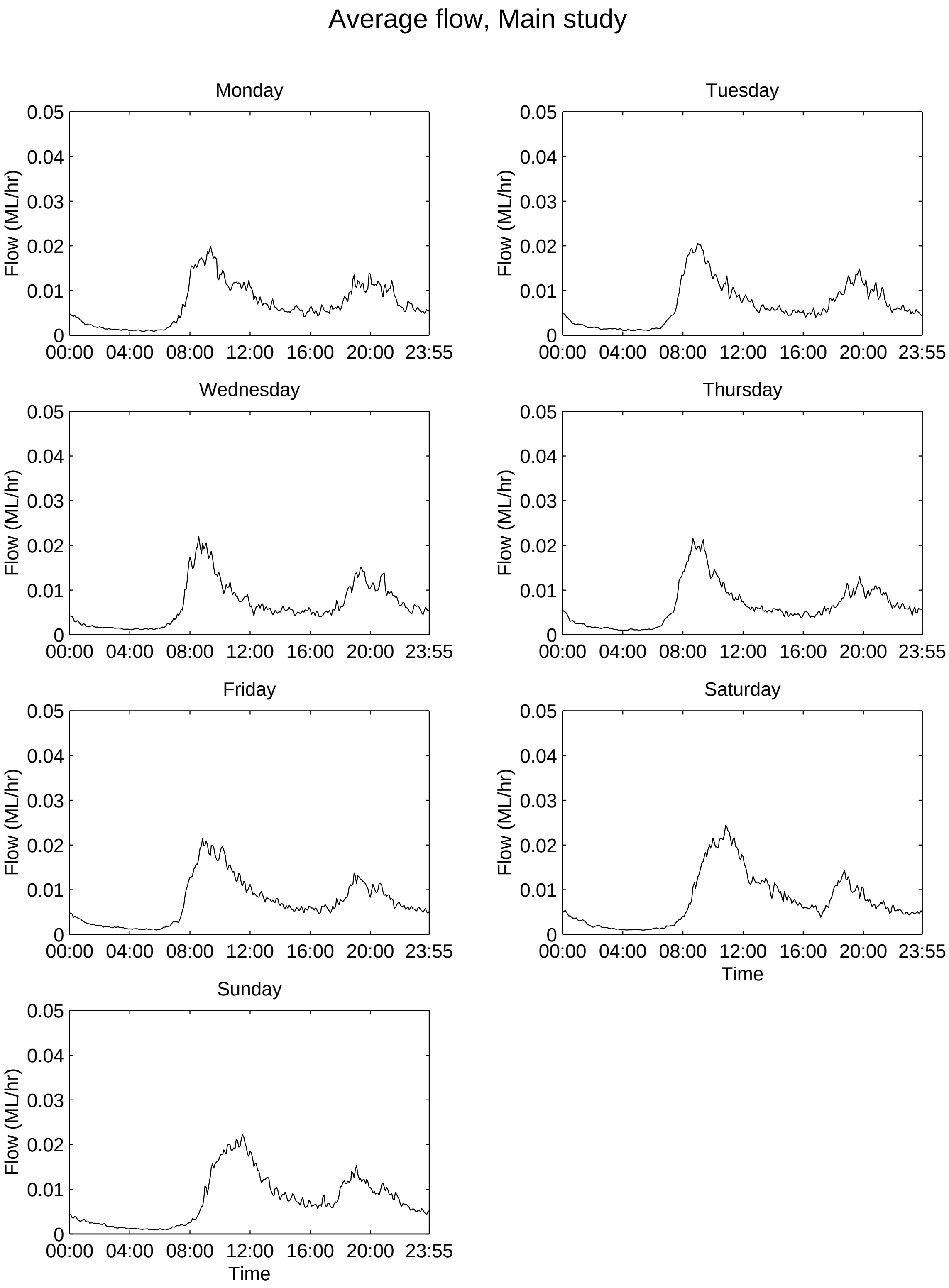

Figure C.5: Average flow per day of week, Main study

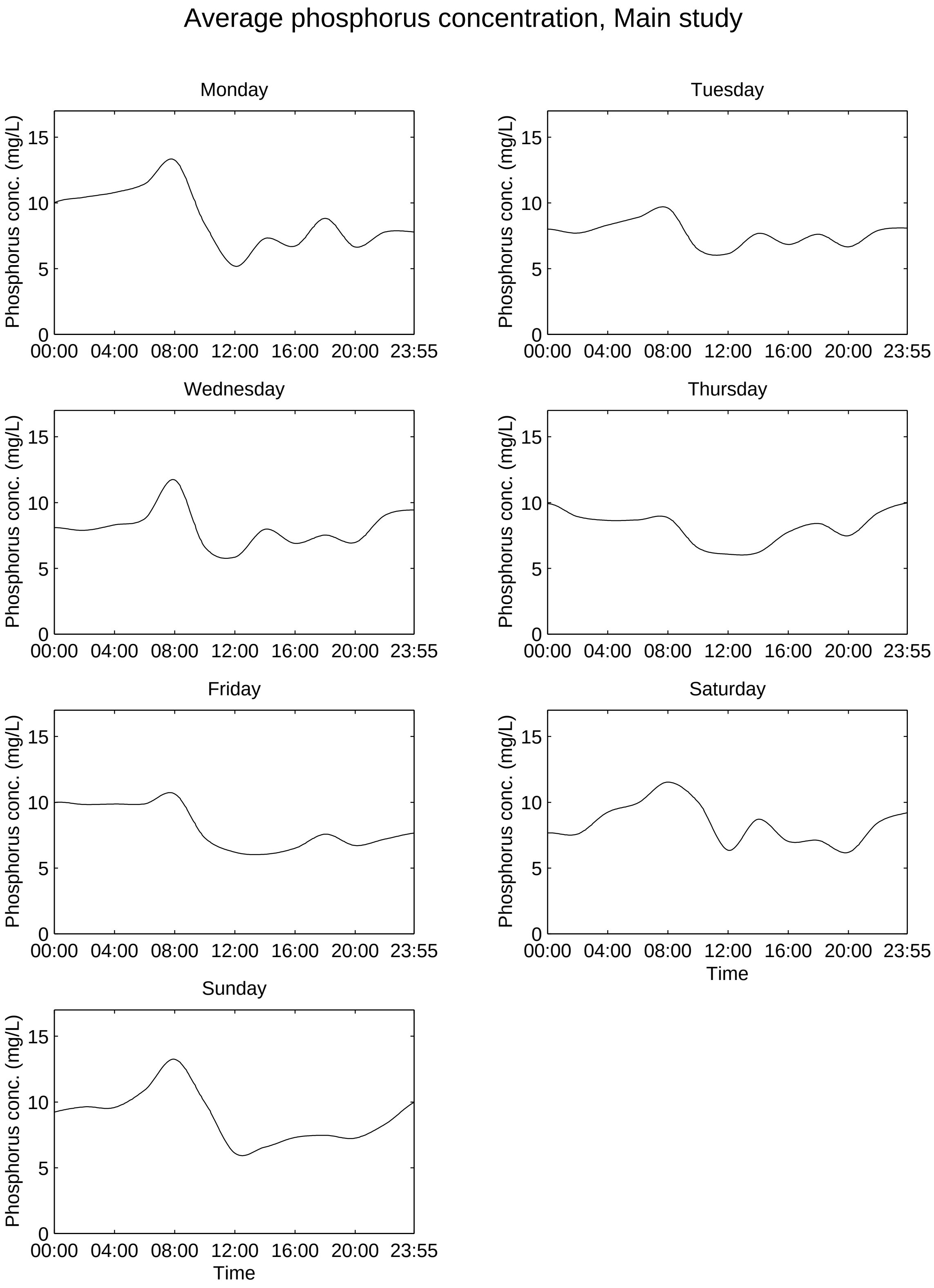

Figure C.6: Average phosphorus concentration per day of week, Main study

Appendix D

Letter to study participants

Appendix E

Pre-study questionnaire

Appendix F

Post-study questionnaire