Impact of Rainfall Events on the Electricity Consumption of Two Wastewater Treatment Plants

Eoin G. Daly
School of Mechanical & Manufacturing Engineering
Dublin City University, Dublin, Ireland
e–mail: eoin.daly43@mail.dcu.ie

Lorna Fitzsimons*, Brian Corcoran
School of Mechanical & Manufacturing Engineering
Dublin City University, Dublin, Ireland
e–mail: lorna.fitzsimons@dcu.ie, brian.corcoran@dcu.ie

ABSTRACT

Focus on the Energy/Water Nexus has led to interest and increased research activity into the relationship between water and society and understanding the energy requirement of Wastewater Treatment Plants (WWTPs) will be a key part of future development. Using wastewater treatment plant data the aim of this paper is to study the relationship between the energy requirements for Wastewater Treatment (WWT), with particular focus on the impact of Wet Weather Flows (WWFs). It has been established from the literature that the efficiency of treatment plant processes drops during these events and, should treatment works be subject to increased energy requirements during WWFs, this will have an impact on any benchmarking effort. Using linear regression, a potential link between increased flows to treatment and electricity consumption of one WWTP in Northern Ireland has been shown, while a second possible link is established between the catchment area rainfall and increased flows to treatment for two WWTPs, which was found to be consistent with previous work in the literature.

KEYWORDS

Wastewater Treatment, Energy/Water Nexus, Water, Electricity, Collection System

INTRODUCTION

Energy use for wastewater treatment

The methods that have evolved for treating wastewater don't come without cost and modern wastewater treatment plants (WWTPs) employ resource intensive processes in terms of energy, chemical and water use [1]. These costs have been the subject of recent research, as aside from the environmental impacts of their use, they represent a cost to water utilities that can be reduced thereby increasing profit or reducing consumer cost [2]. The energy cost of treating wastewater has been shown to account for 1% of the total energy consumption in some European countries, a figure seen to be a good estimate for other European Countries and around the world, and most of this energy requirement goes to power the compressors, pumps, valves and ancillary machinery used in treatment [1,3–5].

* Corresponding author

Variation in WWTP influent

The wastewater that a WWTP can expect to receive is subject to inherent natural diurnal and seasonal variances due to human behaviours and activity, as well as other factors such as catchment area water table level [6]. While this influent may be predicted ahead of time, such as is the case for the plant design phase [7], there are several sources for perturbation that can impact a WWTP during operation such as industrial discharge or power losses, but probably the most common events affecting WWTPs come during periods of wet weather [8,9]. This is a point of critical importance in the future of wastewater management as meeting a standard of consistent plant performance requires the minimising of perturbations due to unexpected or transient events; such events are responsible for noticeable differences in flow to treatment, the consequent effects on plant performance and operation, and can ultimately result in failure of the treatment processes [9,10].

Influence of WWFs

The influence of wet weather flows (WWFs) on wastewater treatment has been a subject of research, although few appear to have focused on the energy requirements to treat such flows. Some of the detrimental impacts on WWTPs have been discussed and reviewed in the literature [6,9–13] and in broad terms it could be said that it is the influence of rainwater on the influent quantity and quality that are of concern to the WWTP operator: volume increases due to inflow and infiltration during events affect the quantity of water to be treated, while changes to the pollutant loads and concentrations affect the quality of the influent. Some of the changes in the influent and effluent quality that have been reported in the literature are shown here in Table 1.

It is to be expected that changes in both the quantity and quality of wastewater being delivered to treatment will have consequences for the energy consumption of WWTPs, with valve operation, increased pumping, aeration changes etc. being required to deal with these flows. Such a change in the energy requirement in operating a WWTP, coupled with any changes to the discharge quality, would inevitably impact on any efficiency metrics employed and would warrant further research. Taken in the context of potential changes in weather patterns due to climate change, this is an important part of the energy/water nexus that should be investigated further.

Table 1. Influent/Effluent characteristics during WWFs

	Influent	Effluent
Flows	Increased flows [6,14] Increased variability [6]	
BOD	Concentrations unchanged/decreased* [11,14] Loads increased (Up to 3x Dry Load) [11]	Concentration increased** [14]
COD	Increased variability (Up to 2x Dry Load) [6] Average 200 kg d-1 (27%) increase [6] Concentrations unchanged or decreased [9,11]	Average 20 kg d-1 increase [6] Increased concentration [9]
TSS	Increased loading [11] Decreased concentration* [9,14]	Increased loading [6,11] Increased concentration*** [9,14]
N	Decreased ammonia concentration [11] Increased ammonia loading [11] Decreased ammonium concentration [9]	Ammonia barely affected [6] Nitrate increased Decreased ammonium concentration [9] Decreased nitrate concentration [9]
TKN	Increased variability [6,9] Increased loading [6] Decreased concentration [9]	Increased concentration [9]

DATA ANALYSIS

Methodology

The approach taken to conduct this analysis was to select a number of plants of similar size with regard to their electricity use and flows to treatment. The electricity consumption over a period of time that would allow for any variations in the flows to treatment owing to seasonal, industrial or other influencing factors between the plants was then compared. A linear regression was conducted to determine if there was a significant relationship between the electricity consumption within the plant and the flow to treatment that had arrived at the plant. A second linear regression was then conducted to investigate the relationship between the rainfall in the catchment area and the flows to treatment received at the WWTP.

* [14] Based on corresponding flow rate increase
** [14] Based on corresponding BOD_{Inf} concentration increase
*** [14] Based on corresponding TSS_{Inf} concentration increase

Treatment plants. The WWTPs used in this study are in Northern Ireland and are operated by Northern Ireland Water (NI Water). Two plants were chosen, after consultation with the staff of NI Water, that would fulfil the necessary criteria and an outline of the processes involved at each plant is shown here in Figure 1.

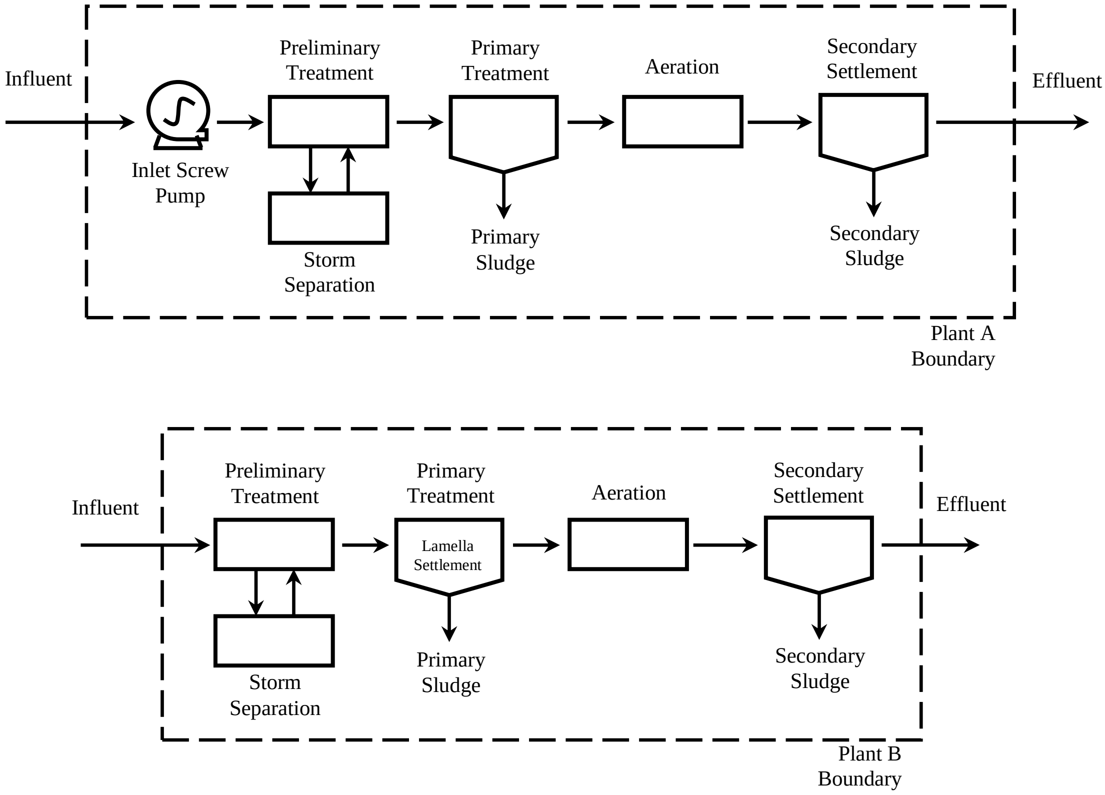

Figure 1. Process Outline for Plants A & B

Plant A has a design capacity of over 85,000 PE while Plant B has a design capacity of 100,000 PE and while both plants are similar the presence of a screw pump at the inlet to Plant A is among the most noticeable differences. The discharge criteria for Plant A and B was also gathered and is shown here in Table 2.

Table 2. Discharge Criteria for Plants A & B

Plant	BOD (mg/l)	Suspended Solids (mg/l)	Ammonia (mg/l)	TN (mg/l)	TP (mg/l)
Plant A	10	20	15	15	15
Plant B	30	50	-	-	-

Despite differing discharge requirements for both plants, consultation with staff at NI Water revealed that Plant B was found in practice to have a discharge quality closer to that of Plant A than would be expected, and so for the purposes of this analysis it was assumed that discharge requirements would not significantly affect the electricity consumption of the plants.

Seasonal breakdown. Restrictions in the amount of data that could be attained from the UK Met Office [15] relating to rainfall meant that the data was divided into two periods between 2016 and 2017. The selection of these seasons was based on early flow data made available by NI

Water and the periods chosen for study were based on periods of relatively high and low flow to treatment. These periods were referred to as the autumn period (September to November) and the spring period (March through May).

Electricity consumption data

The daily electricity consumed in kWh for the two plants was made available by NI Water for both seasonal periods, and cumulative distribution plots were drawn for the total electricity consumed daily across both seasonal periods for each plant, shown here as Figure 2.

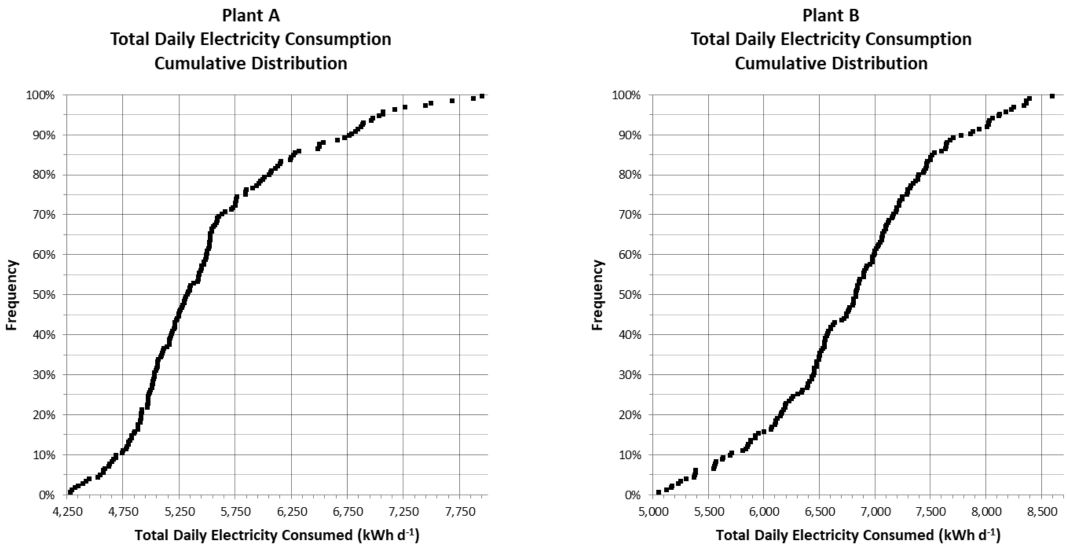

Figure 2. Total Daily Electricity Consumption Cumulative Distributions for Plant A & B

The data shown in Figure 2 shows that, aside from a number of outliers at Plant A, the electricity consumption of both WWTPs is normally distributed. The arithmetic mean and standard deviation were calculated to compare the two plants for electricity consumption which shows that Plant A used on average 5,503 kWh/d across both seasonal periods, with a standard deviation of 756 kWh/d, while Plant B used 6,790 kWh/d with a standard deviation of 765 kWh/d. Plant B's increased mean electricity consumption may be explained by the increased treatment capacity of the plant.

Flow to treatment data

Again using data made available by NI Water the flows to treatment for both plants were plotted as cumulative distributions (Figure 3) which indicated that 90% of the daily flow rates were between approximately 10,500 m^3 and 20,500 m^3 in the case of Plant A, and 12,000 m^3 to 32,000 m^3 for Plant B, reflecting the differing design capacities between the two plants.

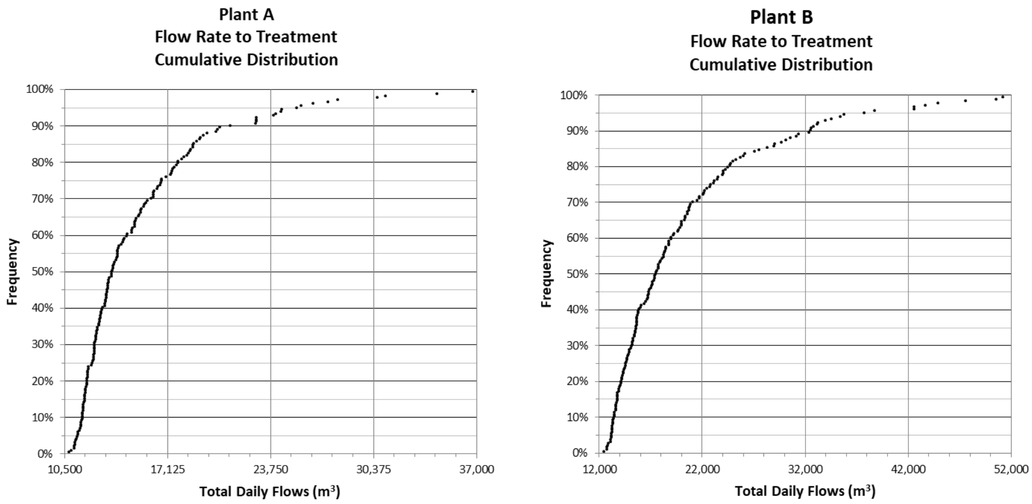

Figure 3. Flow to Treatment Cumulative Distributions for Plant A & B

Both plots in Figure 3 would indicate that, in the case of both plants, there appeared to be significant outliers in the flows to treatment, with the maximum flows being over three times the minimum flow for Plant A and over four times the minimum at Plant B. This would follow some of the information that was found in the published literature during the literature review [11].

Rainfall data

Rainfall data for Northern Ireland was gathered from the UK Met Office [15] and this dataset included the rainfall for several monitoring stations in the region. The selection of which weather station to use was based on an analysis of the location of each in relation to the selected WWTP, with the nearest weather station to the treatment works being selected. Similar methods had been used elsewhere in the literature [14] when analysing the effect of rainfall on the constituents in wastewater after rainfall events and it was felt that it would be appropriate for this analysis also. The rainfall measurements were taken every hour and were to the nearest 0.1 mm, although some periods were recorded as "Trace". For these periods it was assumed that the rainfall lay somewhere between the zero level and 0.1 mm, so such recorded events were given a value of 0.05 mm in order to conduct this study. Each hourly measurement was then summed to give the total daily rainfall in mm for each day from midnight to midnight.

To better compare visually whether the rainfall events were indeed having an effect on the flow to treatment of the WWTP, plots were drawn comparing the rainfall and the flow to treatment at each plant, and the plot for Plant A in Autumn is shown here in Figure 4. The graph indicates that there is a relationship between the rainfall in the catchment area and the flow to treatment at the WWTP, although it does not quantify such an influence and so steps were taken to try to characterise this relationship.

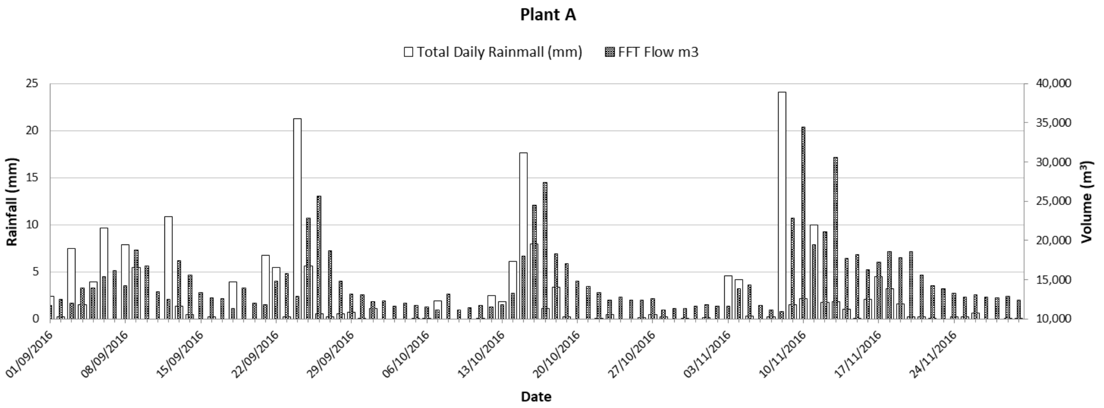

Figure 4. Plant A Rainfall and Treatment Flow Comparison

Electricity consumption vs. flow to treatment

In order to ascertain if there was a relationship between the rainfall in the catchment area and the electricity consumed by the WWTP, a linear regression was carried out. The electricity consumption of both plants was plotted against the flows to treatment for the same day and these plots are shown as Figure 5.

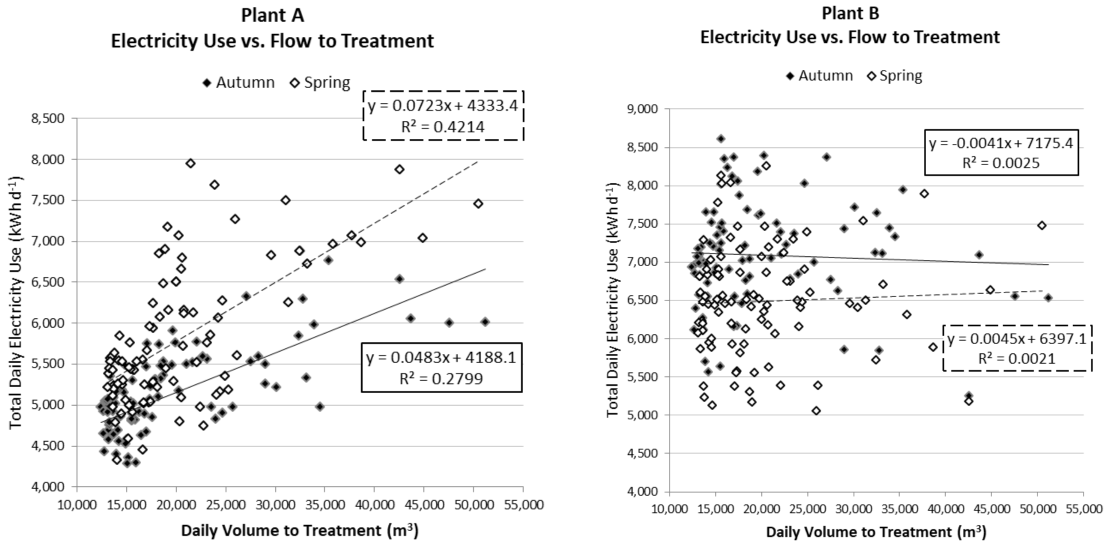

Figure 5. Daily Electricity Use vs. Daily Volume to Treatment

A linear regression on its own is of little use without ascertaining the relevance of the regression, so in order to do so the R^2 values for each line were used along with the values shown in Table 3 that had been outlined previously in the literature to determine the degree of correlation.

Table 3. Degree of Correlation [14]

R^2	Degree of Correlation
0 to 0.04	No or negligible correlation
0.04 to 0.16	Low degree of correlation
0.16 to 0.36	Moderate degree of correlation
0.36 to 0.64	Marked degree of correlation
0.64 to 1.0	High degree of correlation

Using these values it can be seen that linear regressions shown in Figure 5 show a moderate to marked degree of correlation for Plant A, while showing no correlation for Plant B. This result was curious, as it shows that while Plant A increased electricity consumption for increases in the flows to treatment, Plant B does not appear to have any significant relationship between the two. The possible effects of outliers was examined and a decision was made that to discount them entirely would be unwise and so a methodology for smoothing portions of relevant data from the data set was found [14]. This method involved the calculation and plotting of the monthly average rainfall and monthly average flows, but this was modified for use here. This was due to the availability of just six months of data, as it was decided that three monthly averages for each plant and season would be too few for comparison. It was for this reason that the average daily flow to treatment per week and average daily electricity consumed per week were calculated and plotted, see Figure 6.

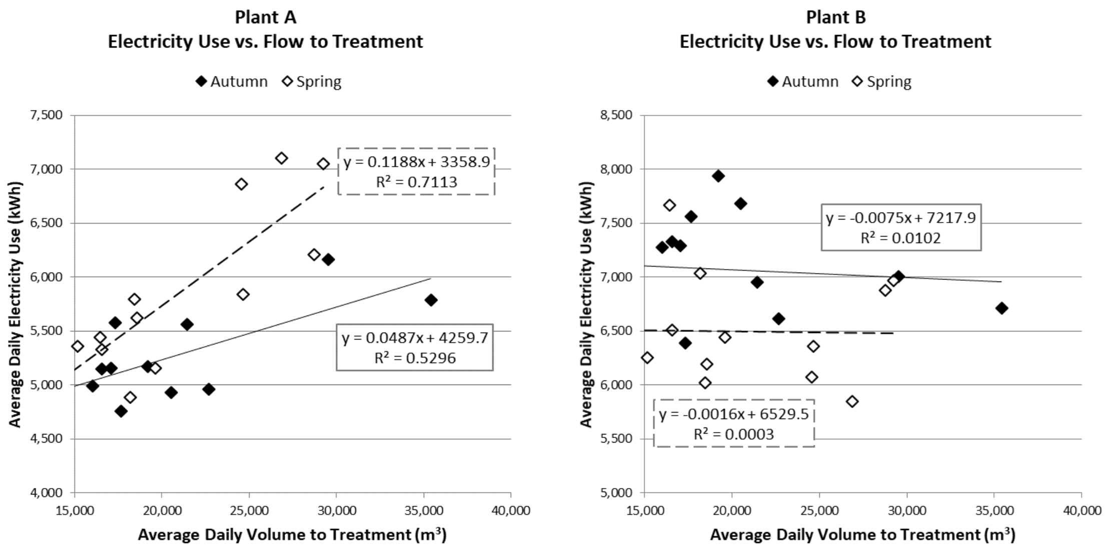

Figure 6. Average Weekly Electricity Use vs. Average Weekly Volume to Treatment

The use of this method yielded a more significant regression for Plant A, but did little in the case of Plant B. This was not entirely unexpected however and discussions with NI Water staff yielded possible reasons for this disparity. As previously stated, Plant A has a large screw pump at the head works prior to treatment and this pump is included in the measurements of electricity consumed by the WWTP. The increase in electrical consumption seen at Plant A could therefore be attributed to these screw pumps engaging due to the increased flows, while similar pumps are not in use at Plant B. In both cases there are several pumping stations along the collection system which are used to pump the wastewater towards the head works. In some cases such pumping stations may negate the need for a large pumping system at the head works of the plant. These terminal pumping stations are not included in electricity data attained from NI Water although they may represent a significant energy use in the system. Where these pumps are located in relation to any energy audits or benchmarking may be of critical importance, as the energy requirement may be significant. Analysis of the electricity required by the entire collection system as well as the WWTP may yield more accurate and comprehensive results in this instance. This issue highlights a fundamental problem with the comparison and benchmarking of WWTPs without accounting for the collection system and WWTP as a whole, as doing so may give a misleading impression of the treatment plant's overall performance.

Flow to treatment vs. rainfall

The quantification of possible relationships between rainfall and the flow to treatment was first attempted by plotting the daily flows against the total daily rainfall, shown here in Figure 7.

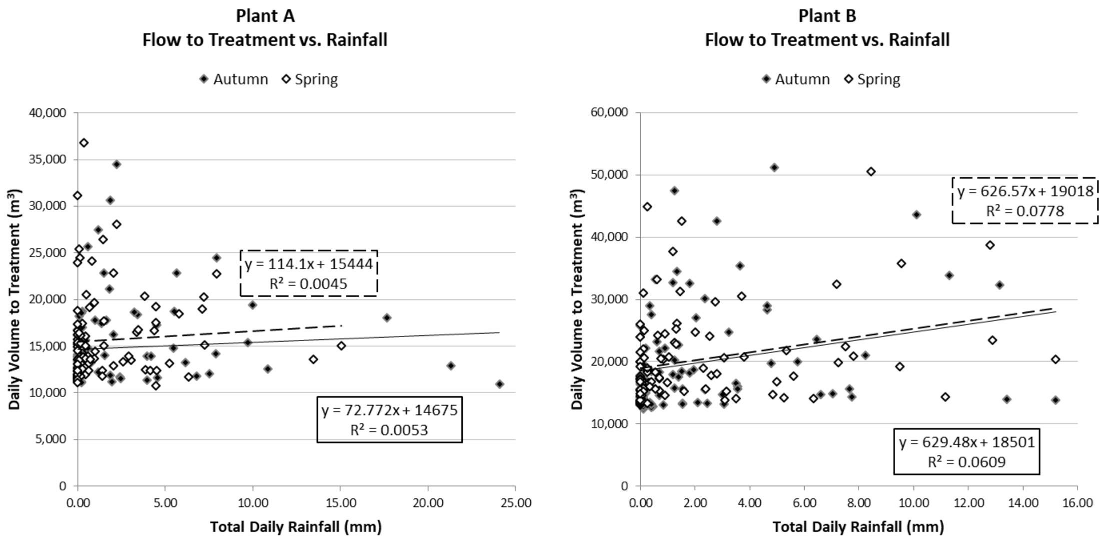

Figure 7. Daily Volume to Treatment vs. Daily Rainfall

What can be seen once again is a linear trend that carries little in the way of significance however, as evidenced by the R^2 values shown, but this time Plant A and B show little or no significant correlation. Again, this was thought to be due to the inclusion of numerous outliers in the dataset, as well as the possibility that the flows to treatment are not reacting on the same temporal scale that is being accounted for in the analysis, that is, a lag exists between a rainfall event and the arrival at the treatment plant head works. This means that rainfall that falls on a single day may not result in an increase in flow on the same day if the rainfall occurs close to the end of the day for example. In such an event, the flow increase would in fact be seen on the following day when the total daily rainfall may be less. This may be further compounded by other issues; while the rainfall measurements are taken from midnight to midnight, the time of measurement for the daily flow to treatment was not recorded in the data made available and may not be consistent across all plants. A similar methodology to the one that had been used to smooth the data for Figure 6 was used and the result is shown here as Figure 8.

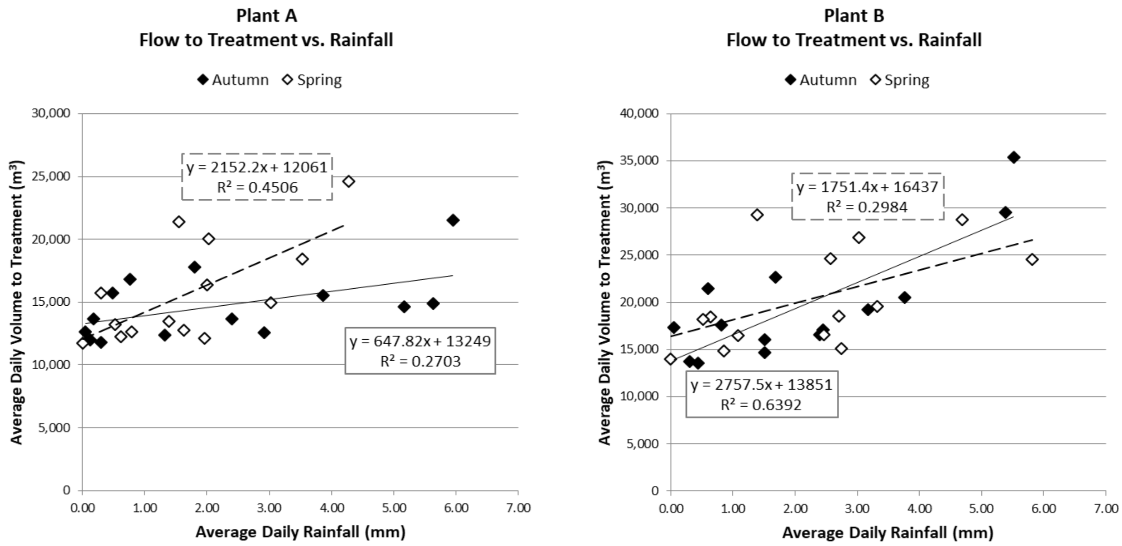

Figure 8. Average Weekly Volumes vs. Average Weekly Rainfall

This method is not ideal and it would be preferred to account for all temporal issues in further work or by refining the datasets available. Having said this, the regressions did produce a moderate to marked degree of correlation in flows to treatment vs. rainfall and where the method used for Figure 6 and Figure 8 had been used previously in the literature reported similar or less significant findings of increases flow to treatment due to rainfall events [14].

CONCLUSIONS

Analysing the behaviour of WWTPs during events such as WWFs may allow for better planning and operation of treatment plants that would be in line with predicted requirements for improved plant performance, as well as dealing with the possible consequences of climate change. The results of this initial study will have implications for any future efforts in the analysis, modelling or benchmarking of WWTPs.

It has been shown that the electricity requirement for WWTP during WWFs increases in the case of one treatment plant in Northern Ireland. It has also been shown that the increased flows due to rainfall did not have any identifiable effect on the electricity consumption of a second treatment plant in Northern Ireland, although this result may be due to a lack of data regarding the collection system and wastewater treatment plant as a whole. Owing to the differences in wastewater treatment practices at a regional and even a catchment area level, it is not possible to draw firm conclusions as to the behaviour of other treatment plants or catchment areas from the results of this study. In the context of energy efficiency, as well as river basin and water resource management, the results of this study indicates the need for the inclusion of the collection system and catchment area details in any assessment of wastewater treatment.

Greater amounts of data and further analysis is necessary to confirm the decrease in plant performance that has been reported in the literature and would allow for a clearer picture of the efficiency during WWFs of the individual WWTPs observed in this study. Process level energy audits coupled with concurrent, high temporal resolution sampling of influent and effluent quality would go some way to providing for this.

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NOMENCLATURE

WWTP – Wastewater Treatment Plant
WWT – Wastewater Treatment
WWF – Wet Weather Flow
BOD – Biological Oxygen Demand
COD – Chemical Oxygen Demand
TSS – Total Suspended Solids
N – Nitrogen
TKN – Total Kjeldahl Nitrogen
NI Water – Northern Ireland Water
TN – Total Nitrogen
TP – Total Phosphorous

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