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THE IMPACT OF BAD SENSORS ON THE WATER INDUSTRY AND POSSIBLE ALTERNATIVES

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SUMMARY: *Advanced monitoring of water quality in order to perform a real-time hazard analysis prior to Water Treatment Works (WTW) is more important nowadays, both to give warning of contamination and also to avoid downtime of the WTW. Downtimes could be a major contributor to risk. Any serious accident will cause a significant loss in customer and investor confidence. In this paper, two treatment plants (case studies) were examined. One was a groundwater WTW and the other a river WTW. The results showed that good correlations existed between the controlling parameters measured at the river WTW, but not at the Groundwater Treatment Works (GWTW), where there was a lack of good correlation between warning parameters. Results emphasised the value of backup monitoring and self-adjusting automation processes that are needed to counteract the rise in power costs. The study showed that a relationship between the different types of sensors and/or measured parameters can be deduced in order to cross-check the sensors performance and be used as a guide to when maintenance is really needed. Operating hierarchal procedures within the WTWs could also be used to cut costs, by improving condition monitoring. Both of the case studies highlighted the need for new non-invasive/remote sensors and some new investment in information technology infrastructure.*

KEYWORDS: *Acoustic-Doppler, Online, Drinking Water, Sensors, Correlations.*

1. INTRODUCTION

The water quality objectives for drinking water treatment works are regulated by the EU Drinking Water Directive (1998). A water treatment works must be able to produce a consistently high quality regardless of the quality of the intake raw water or how great the demand might be. Water treatment consists of a range of unit processes, used in a multi barrier series and this provides some design and operational flexibility to maintain water quality. The treatment required will depend upon raw water quality, which is normally related to its source. In other words, the cleaner the raw water typical of ground water, the fewer treatment steps that are required, and hence the overall cost of water is less (Hughes, 2004).

In 2004, 375 raw water sites were monitored for compliance with the Surface Water Abstraction Directive (75/440/EEC) in England and Wales (UK Environment Agency, 2006). Of these, 155 sites failed to comply with the Directive. However, over 90% of these “failures” were due to insufficient sampling. These sampling shortfalls occur for a number of reasons, such as abstractions not being operated at the time of sampling, analysis problems at the laboratory, and sampling error. The quality of abstracted water was reported to have generally improved since 1993 (EA, 2006).

In order to comply with these regulations (95 % compliance required) and because of spatial and time dependent variability of water characteristics, on-line monitoring would improve this process. Current techniques for measuring water quality involve in-situ measurements and/or the collection of water samples for subsequent

laboratory analyses, which do not however provide data continuously. They achieve accurate measurements for a point in time and space, but are too expensive and slow.(Ritchie & Cooper, 2001).

The automation of WTW systems is not as developed as other process industries. This is thought to be due to the harsh remote environment in which sensors have to be located. The lack of sensors suitable for on-line real-time monitoring is reported to be due to sensors' inconsistency and decay with time (Bourgeois et al., 2001). Investment in monitoring systems is a priority for the industry because it helps the operator with decision-making and performing supervisory control tasks. An important objective for the sponsors of this research was to identify sensor faults, where the sensors are not reliable. In most failure cases in the water industry, the indication of an 'abnormal state' is as a result of a sensor failure rather than a system failure. This caused expensive and unnecessary system shutdowns and maintenance (Alag et. al., 2001), which could help operators improve the monitoring of WTW's processes. It would also assist in understanding how the water industry is coping with the flux of data that is being generated by these sensors.

This paper is based on two water treatment plant case studies, where the impact of bad water sensors in the water industry is investigated, and ways of validating resulting measurements through the use of correlations suggested. Analyses of the results indicated that good correlations existed between the controlling parameters measured at the river WTW, but not at the GWTW. Both of the case studies will also highlight the need for new non-invasive/remote sensors and some new investment in information technology infrastructure.

2. BACKGROUND

The early control systems were designed around telemetry systems for demand management, which have been progressively extended and amalgamated to form very large, highly complex distributed monitoring systems with several thousand remote telemetry units (RTU) and a wide array of different protocols and interfaces. One of the pioneering control systems for WTW was installed by East Worcestershire Water Board in the late 1960s, now absorbed into Severn Trent Water, and was described in the Institute of Electrical & Electronic Engineering evening paper at Savoy Place in 1973. As well as describing the telemetry system, the paper presented work being done with the Cambridge University Department of Mathematics to calculate optimal routing and pump control strategies using an on-line model to achieve efficiency savings. The principal objectives were to optimise the decision making process and to remove the human operator from the loop. Top-end master stations have generally been replaced on a five-to-eight year cycle due to the dependency on software, database and computer technology.

A drive for greater operational efficiency came with privatisation and price control imposed by OFWAT in 1990. An unprecedented level of capital investment was required to meet higher water and river quality standards set by the European Union. The investment in new treatment plants was accompanied by high levels of investment in ICA (Instrumentation Control and Automation), predominantly based on PLC (Programmable Logic Controller) technology, and since 1990, a 50% reduction in staff. A recent survey (National Instruments, 2003) of test and measurement engineers revealed that nearly 20% of the total cost of most data acquisition applications is spent on hardware/sensor set-up and configuration (Fig 1). The estimated worldwide sensor market is expected to exceed $40bn per year by 2008 (Market Report, 1999). Consequently, this would indicate that sensing technology (hardware) and application complexity dictate the cost of an overall measurement; the more advanced the technology and intricate the application, the more expensive the sensor and resulting measurement. However, the introduction of "Plug & Play" sensors (based on the IEEE 1451.4 standard) was a means of standardising sensors design and interface, providing an opportunity for improving analogue sensor performance and usability, while reducing overall cost of ownership. This can be done with smart sensors containing a Transducer Electronic Datasheet (TEDS), which can be queried by a data acquisition system to check the sensor's output without manual interference from the system user. Once the smart sensor is connected, configuration information is electronically transferred to the data acquisition system and the sensor is automatically set-up. In addition to reducing set-up and configuration time, sensor measurement accuracy also improves the ability to remotely validate outputs.

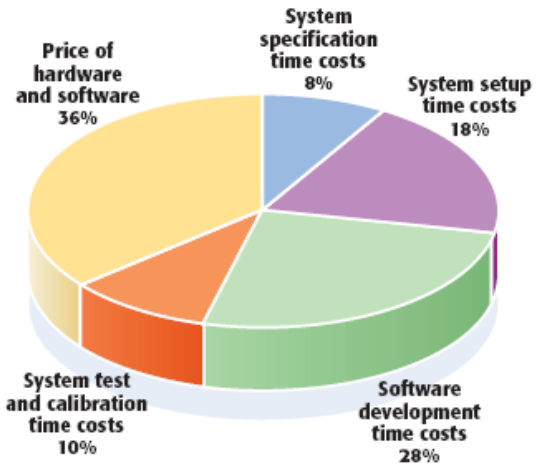

Figure 1: The total cost of data acquisition

Even with the introduction of IEEE 1451.4 standardized technology, there are still a number of factors that make the process of sensor data validation and sensor failure detection difficult. From the process control point of view the plant and process supervision has to fulfil three major tasks (Enste & Uecker, 2000):

1. Validation of process information, which indicates the quality of information and usability. Process information is often used without any validation procedure and process control is sensitive to faulty process information. One wrong measurement or a set of inconsistent measurements can disturb the process and result in a loss of productivity.
2. Supervision of process steps to ensure the desired output quality and behaviour of process values that are relevant to product quality. The multistage approach to WTW makes them less vulnerable to this distortion.
3. Functional reserve, which detects in advance unexpected process disturbances in the future events and changes in the flow process are likely to influence quality. This is particularly important at WTWs, because of the influence of weather.

In order for the plant and process supervision to be able to achieve the three tasks, the sensor network must be trustworthy and dependable. However, factors that can be considered as major obstacles to realising this are, firstly, sensor failures that are masked by normal system manoeuvres or deviations. Subtle sensor failures such as drift are particularly difficult to detect. Secondly, the imperfect nature of the sensors adds noise to the sensors readings (Alag et al., 2001).

Key features are the cost of ownership, which includes reliability and ease of use, as well as the sensor response time and location within the network, are major influences to the water industry acceptance of new and improved sensors technology. The usual technical aspects such as the principles of measurement, reliability, accuracy and detection limits will also dictate whether or not the technology will be accepted and promoted as a standard. Therefore, it is clear that both the performance characteristics (range, linearity, accuracy, response time, limit of detection, etc.) as well as the fundamental properties of the sensors (single or multi-parameter, needed for external sampling and filtration, and intrusive and/or non-invasive techniques) are of major importance when looking at new suitable water methodologies.

Suspended solids load (SSC) or Turbidity levels are one of the most crucial and variable parameters being monitored. Even collecting frequent water samples cannot accurately define a time series of suspended materials, which is often highly variable, both spatially and temporally, and changes with rainfall currents, water depth, and wind effects (Gartner, 2004). These will be one of the main parameters looked at in this paper.

KEY MONITORED PARAMETERS

There are numerous physical, optical & electrochemical water parameters which are critical to the performance of WTWs. Table 1 lists some of these key parameters.

Table 1: Key monitored parameters of water prior to entering Water Treatment Works

Parameter	Measurement method	Description
Salinity	Calculated from conductivity and chloride readings. The best measurements of salinity from conductivity give salinity with an accuracy of ±0.005.	A measure of salt concentration. Salinity measurement assesses the purity of drinking water, monitoring salt water intrusion into fresh water marshes and groundwater aquifers.
Chloride (Cl)	Chloride ion concentration is measured with a number of traditional, wet-chemistry methods (titration), instrumentally (colorimeters), or by correlation with electrical conductivity measurements.	A highly soluble and ubiquitous form of chlorine. Chloride ions are one of the most common ions found in natural waters. Chlorides are abundant in all living cells to maintain osmotic pressure and control communication, e.g. neural transmission.
Conductivity	Conductivity is measured by placing platinum electrodes in water and measuring the current that flows when there is a known voltage between the electrodes. The current depends on conductivity, voltage, and volume of water in the path between electrodes.	As conductivity and ion concentration are highly correlated, conductivity measurements are used to calculate ion concentration in solutions. Conductivity readings determine the purity of water and are used to signal sudden changes in natural water, and to determine how the water sample will react in other chemical analyses.
Colour	Measured by a comparison with a solution of cobalt and platinum.	Coloured water can be typically caused by dissolved organic matter, which absorbs visible light. Apparent colour is due to both light absorption and light scattering. Dissolved matter exclusively causes true colour. Organic matter, which absorbs light within the 300 to 400 nm wavelengths, and some fluoresces in the range of 200 to 400 nm, creates the appearance of colour in water. Typically, these materials are organic in nature and contain aromatic rings.
Flow rate	In general, the Flowmeters can be classified as differential pressure, positive displacement, velocity, and mass meters.	A rate at which a volume of water moves or flows across a certain cross-sectional area during a specified time, and is typically measured in cubic metres per second. Water flow is measured in order to estimate pollutant spread, to monitor groundwater flow, to measure river discharge, to manage water resources, and to evaluate the effects of flooding.
Dissolved Oxygen (DO)	In general, techniques for measuring DO rely on employing an electrode system wherein the dissolved oxygen reacts at the cathode producing a measurable electrochemical effect. The effect may be galvanic, polarographic or potentiometric.	A certain level of dissolved oxygen is required to maintain respiration and biodiversity.
Potential of Hydrogen (pH)	A rough indication of pH can be obtained using pH papers or indicators, which change color as the pH level varies. More accurate pH measurements are obtained with a pH measurement system consisting of three parts: a pH measuring electrode, a reference electrode, and a high input impedance meter.	Expressed as the logarithm of the reciprocal of the hydrogen ion concentration, and is measured on a scale of 0 to 14; 7 being neutral, less than 7 acidic, and more than 7 alkaline. Acid & alkaline conditions are highly corrosive and intervene with transport of water and toxic
Temperature	Temperature can be measured in many ways. Thermistors and mercury thermometers are commonly used. These are calibrated in the laboratory before being used, using mercury or platinum thermometers with accuracy traceable to national standards laboratories. Infrared radiometers on satellites measure the surface of water temperature.	Temperature affects the water's ability to dissolve gases, including oxygen. The lower the temperature, the higher the solubility. Thermal pollution is an artificial warming of a body of water because of industrial discharge of cooling water. This artificially heated water decreases the amount of dissolved oxygen.
Turbidity	When a light beam passes through a fluid sample, the suspended solids scatter the light in all directions (360°spherically). Reduction in the intensity of the light beam is primarily caused by the suspended solids scattering the light. The higher the intensity of scattered light, the higher the turbidity.	Turbidity is measured by shining a beam of light into the solution. The light scattered off the particles suspended in the solution is then measured, and the turbidity reading is most often given in Nephelometric Turbidity Units (NTU) (calibrated against the clay standard of Formazin).
ORP (Oxidation Reduction Potential)	Measured by the difference in electrical potential between a relatively chemically inert electrode and an electrode placed in a solution.	Used to define reactivity odour and oxygen availability. Groundwater is typically low redox since it has been cut off from air. River water on the other hand is high in redox due to saturation. ORP potential is temperature-dependent.

Water pollutants, which are mainly suspended sediment particles or dissolved, contribute towards turbidity. Remote sensing applications to determine water quality are to date limited to measuring conditions that influence and change optical and/or thermal characteristics or electrochemical properties (Ritchie & Cooper, 2001). Remote sensor design is made more difficult by the highly variable sizes of these potential pollutants and the growth and deposition of films and biofilms. Substances (i.e., nutrients, metals) that do not change the optical and/or thermal characteristics of surface waters can only be inferred by measuring surrogate properties (i.e., chlorophylls) or by addition of reactants (Martinez et al, 2004; Jane & Martinez, 2005).

CASE STUDIES

Two case studies were investigated. The sites chosen were based on the two different types of raw water. One site was groundwater with a number of separate boreholes. The second site investigated was a lowland direct river abstraction. This combination of ground and surface water WTW enabled us to compare the demands on the sensors used in these two most common but very different water resources. The hypothesis was to identify whether a possible combination of sensors would make it possible to monitor the WTW more efficiently or whether new alternative sensors would be necessary. Alag et al (2001) reported that by combining information from many different sources, it should be possible to identify correlations and so decrease the uncertainty and ambiguity inherent in processing the information from a single sensor source. A large number of sensors measuring many different variables can collectively achieve a higher level of accuracy and reliability, depending on variability of the correlations between them.

4.1 Groundwater WTW

The research initially had the objective of avoiding false alarms from vulnerable sensors causing shutdown of the WTW. This needed continuous intervention by the operating manager to resolve these problems. The operators covered a large area and a number of remote sites and so the frequency of false alarms was ultimately unmanageable and the sensors switched off. It was also noticed during the study that there was no consistency in the type of qualitative sensors used from the different boreholes. Only two parameters were archived, Fluoride and Phosphate dosage, to comply with most recent requirements set by the regulators. This raised the question as to what parameters were required to comply with regulation and what was necessary for control. Thus it was decided to try and reprocess the data measured, by these two sensors to determine if they could provide more general information about the output.

Three modelled equations based on the Partial Least Square method were extracted for the Borehole1 Flow. Partial least squares (PLS) is a method for constructing predictive models when the factors are many and highly collinear. It was developed in the 1960's by Herman Wold as an econometric technique, and is more commonly used to model chemical engineering processes. PLS has been applied to monitoring and controlling industrial processes; a large process can easily have hundreds of controllable variables and dozens of outputs (Dijkstra, 1983; Geladi & Kowalski, 1986; Stone & Brooks, 1990). Fig. 2 illustrates an example of results of correlations of flow and qualitative data for the three models, with the measured flow versus the calculated flow (for the surrogate sensors) in Mega-litres per day.

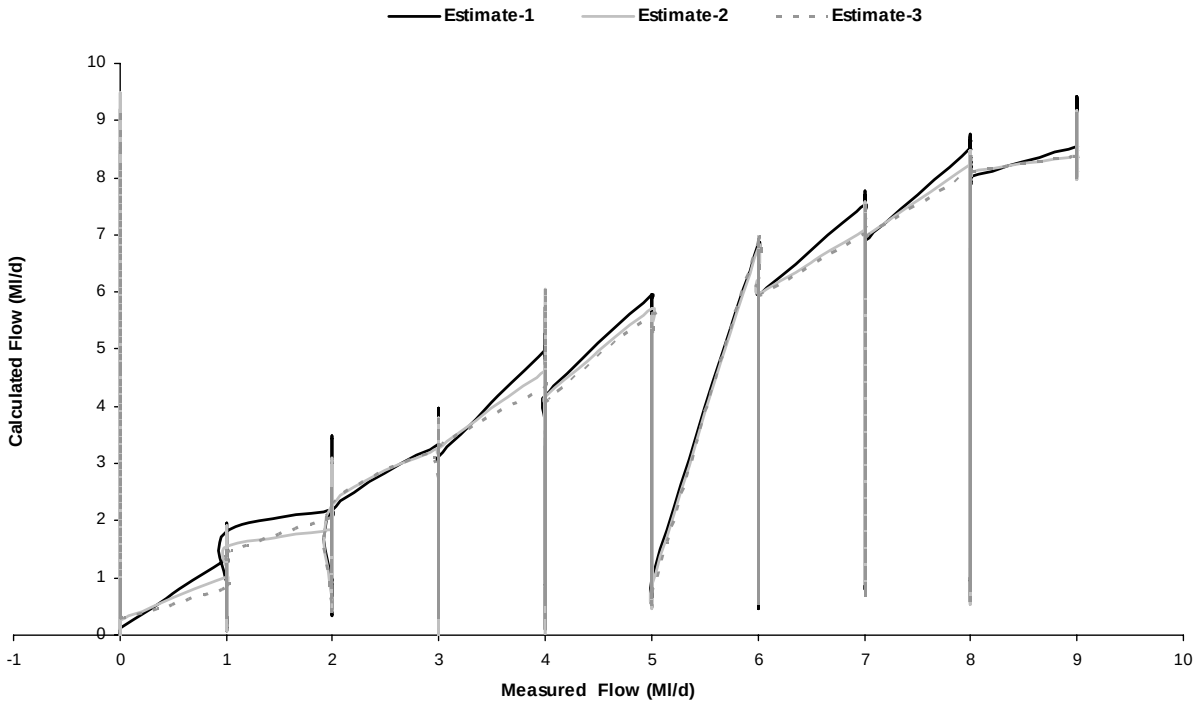

Figure 2: Plot of model predicted using three different correlation models for Groundwater Borehole Flow.

The graphs shown are highly similar in response. Estimate-1 is a calculated response for Borehole1 flow using all of the other measured readings as dependent factors, e.g Reservoir Level, Borehole Flow, etc. In other words, the calculations made included the maximum amount of data independent of its origin. Estimates 2 & 3 used lesser independent data inputs and the resulting correlations seem weaker.

The three graphs showed a strong coherence and indicated the possible use of a very simple equation to predict the total outflow from the WTW and therefore cross-check sensor output. It could help cut the maintenance cost and improve reliability by discarding spurious data under normal operational conditions. The sudden drops in the three graphs were the downtime of the WTW during the experimental period. The analysis indicates that it must also be possible to improve the quality of sensor information by using this type of expert system where a strong correlation can be established.

4.2 River Water WTW

The second objective was to improve the operational reliability of the Supervisory Control and Data Acquisition system (SCADA). The WTW being investigated is a river abstraction of around 100ML/day from a low land river with a flow of 30-100 m^3/s. The site monitors turbidity, colour, pH, conductivity, ammonia & temperature. These parameters were chosen on the basis of their availability and also their relevance to water quality management. Using this data, a partial least squares analysis was performed to try and correlate these data sets together. A positive link was found between turbidity & colour, fig 3. This is understandable; when turbidity is high then other parameters will also increase since sediment load will contribute to the colouring, turbidity and conductivity in the water. It was also found that as expected, the temperature was linked to conductivity readings, as temperature affected solubility of contaminants, and in turn conductivity.

From the analysis, it is also noticeable that there are relations between all the parameters including flow rate. This should not be surprising since an increase in flow is likely to increase the transport and erosion of sediment and turbidity. Previous literature correlating different types of sensors in drinking water were not found and are clearly not used fully. The interrelationship between sensors should be established to crosscheck the other sensor performance. Data gathered does not show how it benefits SCADA or how it links with it. Finally, data from sensors are often disregarded; since operators intuitively find data from grab-wet samples more understandable and reliable.

While analysing the flow data available at the national archive, it emerged that there were two river Derwents whose flow rates were continuously monitored, St Mary's Bridge in Derby, which is considered to be the closest monitoring station to the site being investigated, and a Yorkshire Derwent flow rate at Buttercrambe in York, which is approximately 95 miles to the North-East of Derby. The statistical correlation between the two flow rates, when normalised, was very strong and equal to 0.84. This has implied that there might be less local variations in rainfall than might have been thought. There are also a lot of river obstructions to both rivers which should dampen down this correlation. Obstructions in rivers tend to slow the flow rate of the rivers; hence, reducing any natural flow rates connection between the different rivers.

Using the Least-Squares technique and using the Flow rate of the River Derwent at St Mary's Bridge it was possible to predict the Turbidity trend. Fig. 3 shows the Flow, Turbidity, Conductivity & Colour levels. Fig. 4 illustrates the Turbidity level calculated from just the flow rate at St Mary's Bridge.

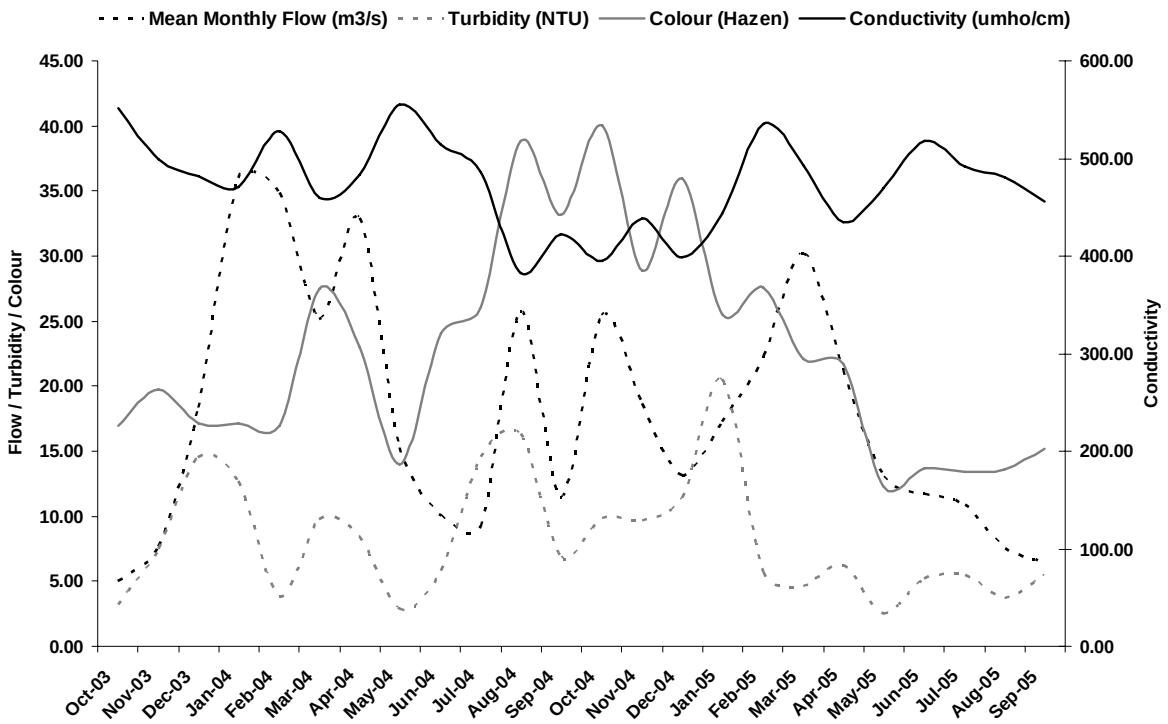

Figure 3: Comparison between Flow, Turbidity, Conductivity & Colour levels measured.

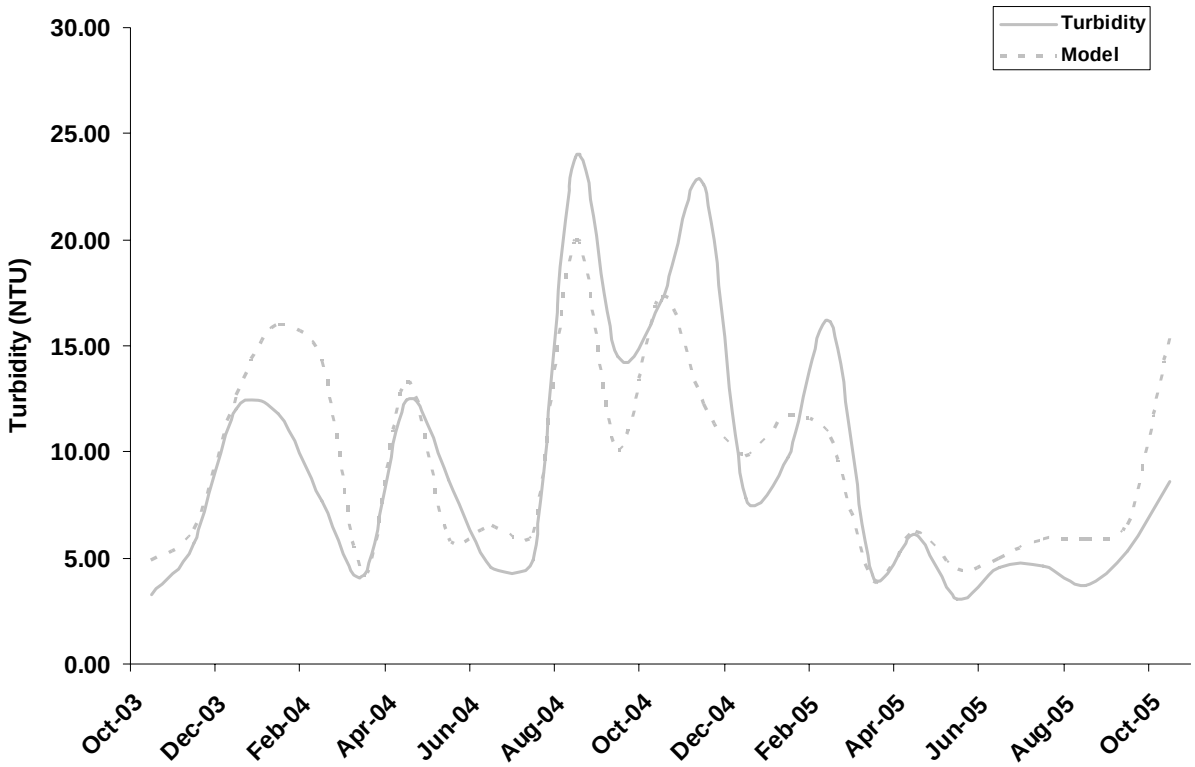

Figure 4: Measured Turbidity levels versus predicted levels extracted from the flow rate at St Mary's Bridge.

Following the derivation of the Turbidity level trend, the data was fed back into the Least-Squares technique, together with the flow data, to predict Conductivity shown in Fig. 5. The trend is not as good as turbidity and flow but is still obvious.

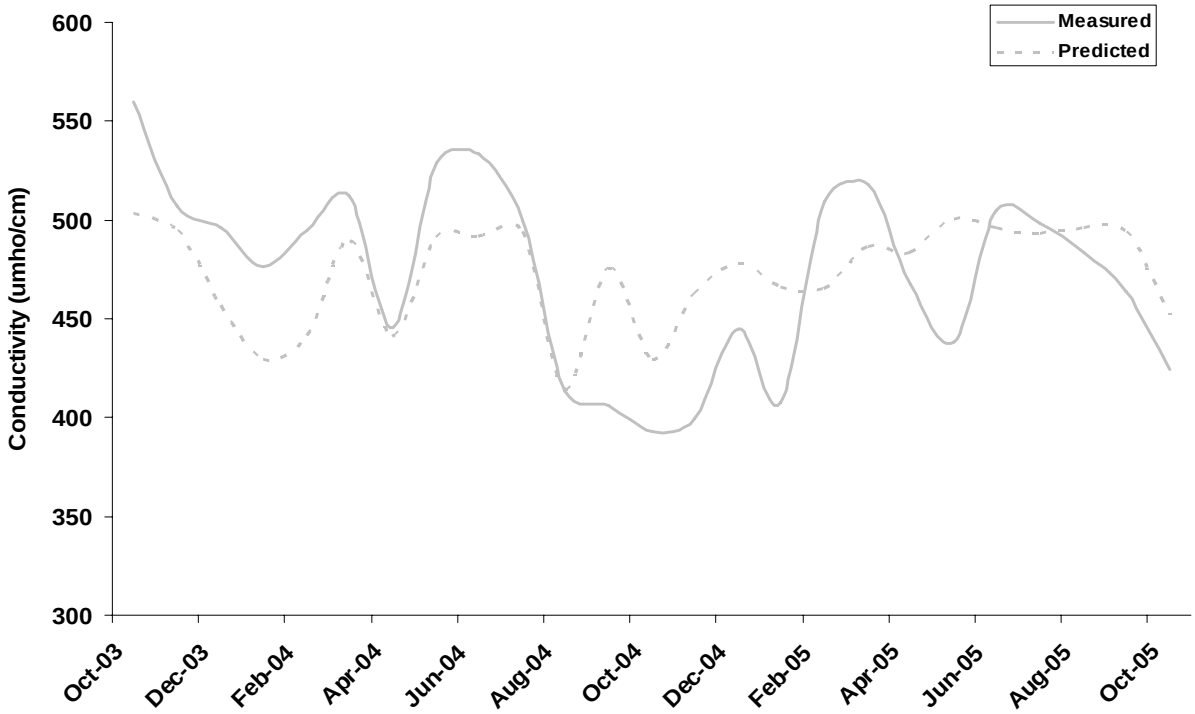

Figure 5: graph of the predicted Conductivity value against the measured value.

The same process was repeated again by using the Conductivity value back into the Least-Squares method to derive the Colour level. In other words, Flow Rate, together with Turbidity Level & Conductivity Values can be used to give Colour Level. Data calculated for Turbidity, Conductivity & Colour could be used as a realistic representation of the current values in the River Derwent more than the current sensors readings. This is because the data calculated is based on the flow of the river, which is more accurate and has a lower error margin during measurements. It should also be stressed that these relationships should be developed as moving correlations over several years and they will not be appropriate coefficients for other WTW, but the procedure is the same. There is at least the prospect of using data from a much wider field of similar rainfalls but with different weightings in the model.

One possible explanation on why the predicted values differ from the measured ones is because the measured values were lab-grab measurements, rather than online measurements. Many operators have more confidence in the grab samples. It is also likely that the correlation coefficient would vary according to flow, season (e.g. leaf fall), antecedent dry period, impoundment, and other river engineering.

LABORATORY ANALYSIS OF SENSORS: ULTRASONIC DOPPLER

Further investigative studies have led the research to look at the possibility of having at least one type of non-intrusive sensor where the previous modelling technique can rely on as an independent-reliable source of data. As the previous sections have shown, it would be logical to look at flow measuring sensors as the possible independent, reliable & non-intrusive sensor.

New innovative remote sensors are being developed and a review of the different types of non-invasive techniques was made (Moustafa et al., 2008). These included acoustic, fluorescence, laser & X-ray techniques. It was concluded that Acoustic-Doppler techniques are the most suitable and cost-effective techniques to be used given the various options. This was based on the fundamental basis of operation, since the technique uses the particles suspended in water to determine the flow velocity of the water. Use of in-situ optical instruments such as optical back scatter (OBS) sensors (Downing et al., 1981; Downing, 1983) and transmissometers with the capability of producing time-series of high-frequency measurements of suspended material help address the variable nature of SSC & Turbidity (Gartner, 2004). However, calibration of these instruments is complicated because the response function of the OBS sensor depends on grain size and is nonlinear with concentration (Downing, 1996). In addition, optical sensors are extremely sensitive to biological fouling problems (Hamilton et al., 1998; Bourgeois et al., 2001). Often, only a few days of data are usable from records collected in highly active reservoirs/lakes unless optical sensors are frequently cleaned. Alternatively, acoustic sensors that are far less susceptible to effects of biological fouling (Downing, 1996; Gartner, 2004) have shown promise for determining reliable estimates of suspended solids (e.g., Thorne et al., 1991; Hay and Sheng, 1992; Osborne et al., 1994). Thevenot and Kraus (1993) and Hamilton et al. (1998) provide extensive comparisons of the strengths and weaknesses of optical and acoustic methods for monitoring suspended materials. While many early studies primarily dealt with suspensions of sand-size materials, some later studies (e.g., Hamilton et al., 1998; Jay et al., 1999) examine the potential for determining suspended cohesive sediment concentration.

As use of acoustic Doppler current profilers (ADCPs) has become more widespread, so have attempts to characterize suspended material from acoustic backscatter intensity measurements made by those acoustic instruments used to measure water velocity (e.g., Thevenot et al., 1992; Reichel and Nachtnebel, 1994). In addition to being less susceptible to biological fouling, commercially available ADCPs may provide non-intrusive estimates of SSC & Turbidity profiles concurrent with measurements of velocity profiles using the same instrument. However, the process of converting backscatter intensity to mass concentration is not straightforward. Among other things, complex acoustic transmission losses from beam spreading and attenuation must be accounted for correctly. They depend on multiple factors including environmental characteristics such as the salinity, temperature, and pressure of the water, and instrument characteristics such as power, transducer size, and frequency. While most early studies utilizing acoustic backscatter to estimate suspended solids typically include beam spreading and water absorption in the calculation of acoustic transmission losses, they often omit corrections for attenuation from suspended particles and non-spherical spreading in the transducer near field. More recent studies have begun to include these factors into consideration. Jay et al. (1999), for example, apply a correction function for improved calculation of beam spreading losses in the ADCP transducer near field to account for the complex acoustic beam pattern, and Holdaway et al. (1999) account for sediment attenuation in their evaluation of ADCPs to estimate suspended sediment concentration.

5.1 Ultrasonic Doppler

The first experiments involved a controlled amount of Bentonite clay powder being added to a water container (approximately 20 litres of tap water). The added amounts were controlled by adding the right dosage equivalent to 5 mg/l at each stage. The turbidity was increased from approximately 0 NTU (clear water) to approximately 30 NTU, which is double the average river turbidity reading measured, Fig 6. The ultrasonic Doppler sensor and an electric stirrer were used to keep the clay in suspension. The Ultrasonic Doppler used was the Nortek Vectrino Velocimeter. The measured flow is practically undisturbed by the presence of the probe, Fig 6. Data was measured at an output rate of 25 Hz. The 3-D velocity range is 2.5 m/s, and the velocity output has no zero-offset.

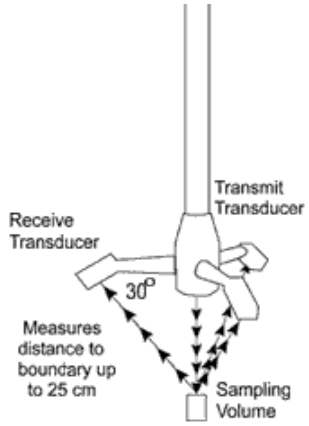

Figure 6: The acoustic sensor used has one transmitting transducer and three receiving transducers, Nortek AS.

The sampling volume of the acoustic sensor is located away from the sensor to provide undisturbed measurements. The Doppler velocity is derived from signals scattered by small particles. In natural bodies of water (streams, lakes, rivers, oceans, etc.) the correlation of particles is sufficient for proper operation. In model tanks with running water (flumes, open channels, closed pipes, etc.) microscopic bubbles in the water column tend to act as natural seeding. In very clean, quiescent water (ship models, tow tanks, and some wave flumes), seeding materials must be added to concentrations of approximately 10 mg/l. The stirrer position was fixed during the entire experimental setup close to the bottom of the tank; so as to ensure that there is no precipitation of the particles at the bottom. The stirrer speed was also fixed in order to ensure that data differences could be attributed to a change in turbidity. Another critical factor during the setup of the probe was to ensure that the side benchmarked as the X-direction on the probe should always be fixed in the direction of the flow. This ensures similar bias from any differences in the sensors.

6. RESULTS & DISCUSSION

Fig. 7 demonstrates that the probe was capable of quantifying the amount of turbidity particulates flowing in the water. However the only setback associated with the experiments was that the test graphs did not improve despite repeated trials. This still leaves the possibility that the sensitivity of the probe was too low to measure changes in turbidity levels in groundwater or final treated water. To put it in perspective, this measuring technique would be more suitable to be used in river or surface water sources. This is because one would expect turbidity to be high enough for the sensor to measure from these sources. Alternative water sources or final water produced from WTW would be very difficult for the sensor to measure its turbidity, since they are understandably low on turbidity. Nonetheless, the probe was more than capable of measuring high turbidity levels quite accurately.

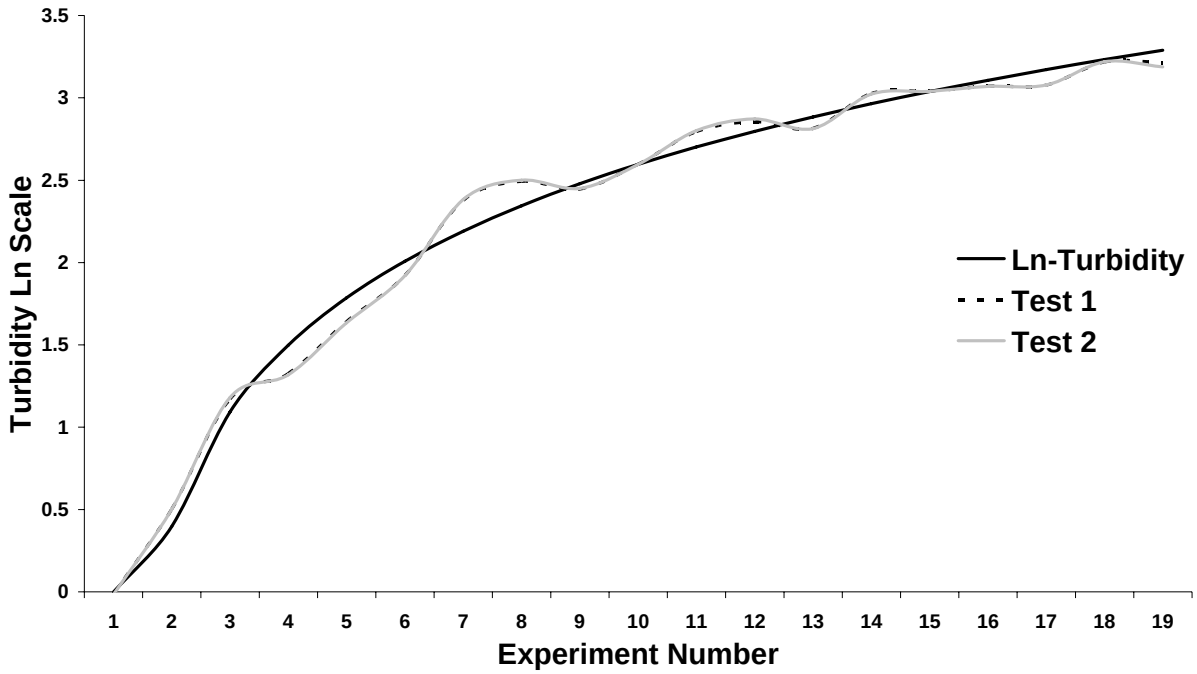

Figure 7: comparison between the measured turbidity levels versus readings taken by the Ultrasonic probe after applying PLS to the readings

It is sufficient to say that there is a lack of confidence from the sensors and data collected at the WTW sites. In one of the case studies, the sensors were actually a major burden on resources (false alarms and associated costs) rather than being the dependent analyser. Correlations were established between the different types of sensors, i.e. chemical and physical (flow) which does offer the possibility of better models with inbuilt deletion of spurious data. This would eventually lead to enhanced control of the water treatment works. Correlations were also found between river flows in two different rivers 150km apart indicating the possibility of value in a National network of sensors. A modern non-invasive probe technology, in this case the Acoustic Doppler, was also investigated to provide data which could be interrogated differently to achieve qualitative as well as quantitative data.

CONCLUSION

Two case studies were examined to try and investigate the impact of sensors currently being used in the industry on the overall performance of a water treatment works. One river abstraction Water Treatment Works and one groundwater Treatment Works were probed. The findings presented for the two sites showed the lack of understanding of the sensors capability and exposed the operators' mistrust in these sensors readings. The study also showed the potential use & benefits, if this study had been investigated much earlier, to the water industry. It also highlights the full potential of an alternative measuring and monitoring technique that can be implemented within the industry. Results emphasised the issue of backup monitoring and self adjusting automation processes that are needed. The study revealed that a relationship is needed to be found between the different types of sensors and/or measured parameters in order to cross-check the sensors' performance and be used as a guide of when maintenance procedures are needed.

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REFERENCES

Alag S., Agogino A.M., Morjaria M. (2001). A methodology for intelligent sensor measurement, validation, fusion and fault detection for equipment monitoring and diagnostics. *Artificial Intelligence for Engineering Design, Analysis and Manufacturing*, 15, 307–320.

Bourgeois W., Burgess J. E., Stuetz R.M. (2001). Review: On-line monitoring of wastewater quality: a review. *Journal of Chemical Technology & Biotechnology* 76, pp. 337 – 348.

Council Directive 98/83/EC on the quality of water intended for human consumption. (1998). *Official Journal L 330, 003 -0054. http://eur-ex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:31998L0083:EN:HTML*

Dijkstra T. (1983) Some comments on maximum likelihood and partial least squares methods. Journal of Econometrics, 22, 67-90.

Dolgonosov B. M., Korchagin K. A. (2005). Statistical assessment of relationships between water flow in a river and water turbidity in water intakes. *Water Resources*, vol. 32, no. 2, pp. 175-182.

Downing J.P. (1983). An optical instrument for monitoring suspended particles in ocean and laboratory. *OCEANS* 1983, pp. 199 – 202.

Downing J.P. (1996). Suspended sediment and turbidity measurements in streams: What they do and do not mean. Automatic Water Quality Monitoring Workshop, Richmond, B.C.

Downing J.P., Sternberg R.W., Lister C.R.B. (1981). New instrumentation for the Investigation of sediment suspension processes in the shallow marine environment. *Marine Geology* 42, pp. 19 – 34.

Enste U., Uecker F. (2000). Use of supervisory information in process control. Special Feature Intelligent Sensors, *IEE Computing & Control Engineering Journal*, pp. 234 – 241.

Environment Agency Website. (2004). *http:// www.environment-agency.gov.uk/.*

Gartner J.W. (2004). Estimating suspended solids concentration from backscatter intensity measured by acoustic Doppler current profiler in San Francisco Bay, California. *Marine Geology* 211, pp. 169-187.

Geladi P, Kowalski B. (1986) Partial least squares regression: A tutorial. Analytical Chimica Acta, 185, pp. 1-17.

Hamilton L.J., Shi Z., Zhang S.Y. (1998). Acoustic backscatter measurements of estuarine suspended cohesive sediment concentration profiles. *Journal of Coastal Research* 14, pp. 1213 – 1224.

Hay A.E., Sheng J. (1992). Vertical profiles of suspended sand concentration and size from multi-frequency. *Journal of Geophysical Research* 97, 15, pp. 661 – 15,677.

Holdaway G.P., Thorne P.D., Flatt D., Jones S.E., Prandle D. (1999). Comparison between ADCP and transmissometer measurements of suspended sediment concentration. *Continental Shelf Research* 19, pp. 421 – 441.

Hughes G. (2004). Standardising Control for the Water Industry. *Computing and Control Engineering Journal*, vol 15, issue 5.

Jane K.H., and Martinez K (2005). Environmental sensor networks, *Eos*, Volume 86(16) page 162.

Jay D.A., Orton P., Kay D.J., Fain A., Baptisa, A.M. (1999). Acoustic determination of sediment concentrations, settling velocities, horizontal transports and vertical fluxes in estuaries. Proceedings: 6th Working Conference on Current Measurement, pp. 258– 263.

Market Report. (1999). *Sensor Markets 2008*. By Intechno Consulting.

Martinez K, Hart J. K., Ong R. (2004). Environmental Sensor Networks. *Computer*, vol. 37, no. 8, pp. 50-56.

Moustafa A., El-Hamalawi A., Wheatley A.D. (2008), Review of measurement sensors in the water industry, Water Science & Technology, in preparation.

National Instruments survey of data acquisition engineers and technicians. (2003).

Osborne P.D., Vincent C.E., Greenwood B. (1994). Measurement of suspended sand concentrations in the nearshore: field intercomparison of optical and acoustic backscatter sensors. *Continental Shelf Research* 14, pp. 159 – 174.

Reichel G., Nachtnebel H.P. (1994). Suspended sediment monitoring in a fluvial environment: advantages and limitations applying an acoustic Doppler current profiler. *Water Research* 28, pp. 751–761.

Ritchie J.C. and Cooper C.M. (2001). Remote sensing for determining water quality: Application to TMDL, pp. 367-375. In: TMDL Science Issues Conference, Water Environment Federation, Alexandria, VA, USA.

Stone M. and Brooks R. (1990). Continuum regression: Cross-validated sequentially constructed prediction embracing ordinary least squares, partial least squares, and principal components regression. *Journal of the Royal Statistical Society*, Series B, 52(2), 237-269.

Thevenot M.M., Kraus, N.C. (1993). Comparison of acoustical and optical measurements of suspended material in the Chesapeake Estuary. *Journal of Marine Environmental Engineering* 1, 65– 79. Gordon and Breach Science Publishers.

Thevenot M.M., Prickett T.L., Kraus N.C. (1992). Tylers Beach, Virginia, dredged material plume monitoring project 27 September to 4 October 1991. *Dredging Research Program Technical Report* DRP-92-7, US Army Corps of Engineers, pp. 204.

Thorne P.D., Vincent C.E., Harcastle P.J., Rehman S., Pearson N. (1991). Measuring suspended sediment concentrations using acoustic backscatter devices. *Marine Geology* 98, pp. 7 – 16.