WATER RESEARCH

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J H Warden
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SMALL SUPPLY SYSTEMS - EFFECT OF VARIABILITY OF RAW WATER QUALITY

Final Report to the Department of the Environment

DoE Contract PECD 7/7/198
WRc Project PWT 9880

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EXECUTIVE SUMMARY

Every processing plant operating as an independent unit, whether it is a waterworks, sewage works, engineering factory or retail warehouse, needs to be able to handle a varying load. Every kind of business is under continuous pressure to improve economic efficiency. The key to success lies in providing the right combination of capital equipment, operational resources and stock holding together with a management system capable of achieving optimum results under all conditions. If the load is well enough characterised, it should be possible to predict the performance to be expected under different conditions and to set performance standards. It may even be possible to contemplate an allowable degree of under-performance or even an acceptable failure rate at times of peak load.

The concept is not new, but it was this which prompted the initiation of this research related to small water supplies.

This is the second of two related reports. The first reviewed what was known about the variability of water quality at small supply sources. This report reviews treatment processes appropriate to small supplies and how they may be selected according to the nature of the source.

It has been found that in the design of small treatment works, there is no systematic methodology for describing the variability of raw water quality and only the most rudimentary methods of selecting processes and designing plant to take account of the variability of the source. The same situation is found in the design of large waterworks and indeed of process plants of all kinds. In many process industries the approach is to control feedstock quality or, where it is a natural material to homogenise it. It has been found that variability is so little regarded in the design of process plant that even an adequate means of describing it does not exist.

The report makes suggestions for further work, not necessarily to be sponsored by the Department of the Environment.

CONTENTS

1. INTRODUCTION

An important aspect of the quality of a drinking water supply is that it should be consistent. Consumers in a district become accustomed to the quality generally supplied and tend to regard any change as a deterioration, even if the supply still meets its targets; sometimes, even if the change is an actual improvement.

It has to be admitted that in the case of small public supplies, quality variations do not always remain within the bounds of acceptability defined in the Drinking Water Directive (1). For instance, Buckley (2) reported how in Welsh Water Authority, while the annual trend in bacteriological quality from 1979 to 1983 had shown an increase in compliance from 95% to 97%, there were still enough unsatisfactory samples to cause concern and that most of these were taken from rural supplies.

While some part of this problem can be attributed to equipment failure, it appears likely that a major part is due to the installed processes and equipment being simply unable to cope with the range of variations in the quality of the raw water from surface sources.

A prior report (3) found that although there was active research into the mechanisms affecting stream water quality in small catchments, it was not directed primarily at drinking water applications. In fact there was no significant body of data on the variability of water quality in small water supplies such as would be of assistance in designing treatment improvements. That report mentioned two models under development and suggested that with straightforward development it should be possible to produce a model which would predict how the water quality at a stream intake would change in response to rainfall.

Anticipating a more substantial outcome of the prior study, the present study was commissioned to investigate the ways in which small supply treatment processes respond to changes in raw water quality and so develop a system for process selection that could be applied to the many hundreds of small supplies in need of improvement.

2. CONTRACT OBJECTIVES

To characterise the treatment processes used on small supplies and particularly the degree to which they reduce the range of quality variations as water passes through, so as to provide the means of selecting process routes appropriate to different types of raw water source.

3. PROGRAMME OF WORK

List and classify the simple filtration and disinfection processes and equipments used or appropriate to small drinking water supplies, both public and private.

Obtain and study operating records and design data so as to identify for each the range of operating conditions over which it is able to maintain steady and satisfactory treated water quality. Where information is not available, attempt to arrange (at no cost to the project) for sampling and analyses to be performed.

Examine the collected data and if possible develop a numerical system of performance rating which takes into account variations of turbidity, colour and bacteriological quality.

Relate criteria derived to information obtained in DoE contract PECD 7/7/154 on quality variations in small supply sources (3).

Propose a method of process selection according to the quality and variability of a small supply source.

Provide final contract report on completion.

4. FINDINGS

The list of processes appropriate to small or private water supplies is much the same as the list of processes used on major supplies although the frequencies of use are quite different in the two lists, and some indication of this is given in the remarks below.

In the operation of water treatment plant over several decades, a body of informal and largely undocumented knowledge has grown up in the industry concerning the performance of water treatment processes at different loading rates. Most of this relates to steady state conditions or to averages taken over some period.

The programme of work included a study of waterworks operating records for evidence as to how processes responded to change. Nothing significant was found. It is noted that, since the purpose of waterworks is to produce potable quality water, monitoring and records are concentrated on final water quality. Where information about plant performance can be gathered, it is usually a byproduct of the archive and rather sketchy. The exception to this is energy consumption which is closely monitored.

Operating records on small supplies consist generally of weekly or sub-weekly notes of chlorine residuals interspersed by routine monthly or quarterly chemical and bacteriological analyses and less frequent examinations of raw water. For example in one division of one of the Scottish Regional Councils there were only two samples of treated water and one of raw water examined each year per supply.

On larger waterworks the daily log usually records chemical dosage rates, times of filter washing and regular checks on the quality of treated water going into supply. The parameters recorded usually include turbidity, colour and chlorine residual together with others that may be of concern in the particular supply, such as aluminium, nitrate, chlorophyll.

It was discovered in the first part of the contract that surprisingly little information was recorded, even on large works, on raw water quality. There was certainly none which characterised variability on an hour by hour basis such as could be related to plant performance. The following information about 16 treatment processes appropriate to small supplies, therefore, summarises the best that can be said, drawn from visits to sites and conversations with attendants, supervisors and those responsible for the control, design and furnishing of small supplies.

4.1. Storage before treatment

Functions

- maintain continuity of supply when demand exceeds source flow,
- enable intake to be closed at times of low water quality,
- improve water quality before treatment.

Description

Water is drawn from the source and stored in a small lake or reservoir which, on a small supply may be covered or uncovered. The capacity may vary from about 12 hours' supply in a covered tank to some weeks' supply in an open reservoir. Allowing solids to settle improves both clarity and bacterial quality (because bacteria associate with solids). The natural ecological system in an open reservoir will purify by biological oxidation and exposure to the ultraviolet content of daylight will inactivate bacteria.

Where the raw water contains sufficient nitrogen and phosphorus, algae may develop and the reservoir become a nutrient store. In such a case the nutrients might be removed by coagulation or limited by controlling the intake.

Applications

Not widely practised on small supplies, mainly applicable to lowland supplies where, also, the algal problems are greatest.

Performance

Assessed in laboratory or pilot tests; little effect on solutes.

Disturbed by

Exposure to strong winds will suspend sediments. Fallen leaves can block equipment and decaying vegetation cause tastes and odours. Problems of short-circuiting and stratification.

Response to variable quality of input

The prime function is to buffer variations in demand. Quality variations are also smoothed where there is natural mixing.

Alternative processes

Gravel prefiltration for solids removal.

Continuity of supply can also be provided by storing treated water.

Cost of ownership

Cost of construction can be substantial. Supervision and maintenance can not be neglected.

4.2. Screening

Function

Remove gross solids from intake

Description

Water from a surface source flows through a mesh, usually of parallel vertical bars of plastic or steel at between 20mm and 80mm spacing. Solids retained on the upstream face are removed manually or, in some cases, by the flow of the stream from which the abstraction is made.

Applications - actual, preferred

Any surface source where large waterborne solids are likely to be drawn in to the treatment plant, but not common on small supplies.

Alternative processes

Careful siting and design of intakes can reduce the need for screens.

Cost of ownership

Not excessive but can be a nuisance.

4.3. Plain Sedimentation

Function

Reduction of turbidity and suspended colour usually before filtration.

Description

Water enters an open rectangular tank at one end and overflows at the other. The area of the tank is normally designed to allow for the removal of all settleable material from the flow. Sediment is removed periodically.

Applications - actual, preferred

Few small supplies are taken from sources which are usually turbid, but there are many which are turbid occasionally, some of these provided with plain sedimentation tanks.

Plain sedimentation should be considered as a preliminary to slow filtration where the raw water turbidity is consistently more than 4 NTU and frequently more than 10 NTU. It might also be considered for use on its own where the source water is normally of low turbidity but subject to occasional flashes. It is most effective where the source is on high ground and turbidity consists of silt and vegetable debris. It is less effective on water loaded with colloidal solids.

Performance

Has potential to remove all solids sedimented in cylinder test; typically removes 50-90% of turbidity and bacteria.

Disturbed by

Wind can impair settlement and even resuspend sediments. Airborne contamination can include dead leaves and bird droppings.

Response to variable quality of input

Variations are reflected but on a reduced scale.

Alternative processes

Gravel prefiltration (below) is more costly but removes colloids better.

Cost of ownership

Moderate.

4.4. Gravel prefiltration

Function

- Reduction of turbidity and suspended colour,
- reduction of BOD and bacterial load;

  usually before filtration.

Description

A rectangular channel is filled with gravel, often in three sections ranging in size from 30mm to 4mm, water flowing from coarse to fine. Solids are removed by sedimentation and surface action and a bacterial action can develop to further enhance water quality.

Applications - actual, preferred

Recently-developed process, not many existing installations. Rather more expensive than plain sedimentation (above), is more effective for removing colloidal turbidity and BOD from lowland waters. It should be considered where the raw water turbidity is consistently more than 4 NTU and frequently more than 10 NTU.

Performance

Typically removes 5% dissolved colour, 50-80% turbidity and bacteria.

Disturbed by

Airborne contamination and dead leaves, not much by wind. Where there is bacterial action, it is important to ensure that a sufficient dissolved oxygen content is maintained - or else replaced at outlet weir.

Response to variable quality of input

Turbidity variations will be transmitted on a reduced scale. Bacterial action will respond only slowly to changes.

Alternative processes

Plain sedimentation (above) is cheaper but less effective on colloids and BOD.

Cost of ownership

Moderate

4.5. pH adjustment by chemical dosing

Function

To reduce corrosivity of water.

Description

Natural waters are hardly ever excessively alkaline but can be acid and, if low in dissolved carbonate species, can be subject to wide pH fluctuations as carbon dioxide content varies. Caustic soda or sodium carbonate solutions are dosed.

Applications - actual, preferred

Caustic soda rarely used but sometimes added to sodium hypochlorite to stabilise disinfectant and combine pH adjustment with disinfection. Carbonate or bicarbonate dosing is generally preferable to increase buffering.

Performance

Potentially completely effective given good dose control. Increasing pH will increase intensity of any colour present.

Response to variable quality of input

Depends upon measurement of input pH and corresponding dose control.

Alternative processes

Contact beds (below)

Cost of ownership

Relatively high in capital and revenue.

4.6 pH adjustment in contact beds

Function

To reduce corrosivity of water.

Description

Natural waters are hardly ever excessively alkaline but can be acid and, if low in dissolved carbonate species, can be subject to wide pH fluctuations as carbon dioxide content varies. Passage through a granular bed of natural calcium carbonate or manufactured medium, e.g. semi-calcined dolomites, removes acidity and confers buffer capacity.

Applications - actual, preferred

Not in widespread use but in recent years several supplies have been improved by addition of a layer of manufactured material to a filter.

The manufactured materials containing magnesium oxide and calcium hydroxide dissolve readily enough to over-elevate pH unless contact time is limited. Natural materials require longer contact but reach equilibrium at acceptable pH.

Performance

Capable of achieving target. Increasing pH will increase intensity of any colour present.

Disturbed by

Release of insoluble fines, precipitate fouling and (for manufactured media) stagnation of flow.

Response to variable quality of input

Fully tolerant of all natural pH variations.

Alternative processes

Chemical dosing (above).

Cost of ownership

Low.

4.7. Coagulation

Function

- Precipitation of colour,
- aggregation of colloids.

Description

Coagulant chemical solution is dosed into the flow and thoroughly mixed. The coagulant precipitates a floc which co-precipitates, adsorbs and entraps colour, vegetable and mineral particles and microorganisms. This floc is removed by filtration, preceded if necessary by sedimentation, and later discharged as sludge.

Applications - actual, preferred

Not widely used on small supplies, may be necessary where excessive colour cannot be avoided or removed in any other way.

Performance

Can capture more than 99% removable material, but success depends also on floc removal processes.

Disturbed by

Fluctuations in water pH, alkalinity and in load of removable matter, especially colour.

Response to variable quality of input

Requires immediate and sensitive adjustment of dose and pH for best results, especially on waters with little buffering capacity.

Cost of ownership

High.

4.8. Sedimentation (following coagulation)

Function

To remove floc where the load is too great for filtration alone.

Description

In horizontal flow, water enters an open rectangular tank at one end and overflows at the other. The area of the tank is normally designed to allow for the removal of all settleable material from the flow. Sediment is removed periodically.

In upflow, water enters at the base of a tank and overflows into a collecting launder. Floc accumulates below a horizon in a fluid "blanket" where fine material is trapped which might be lost in horizontal flow. Intermittent bleed from the blanket maintains a steady state. Means of sludge disposal is required.

Applications - actual, preferred

Virtually unknown on small supplies, may be needed to reduce load on filters where upgrading introduces coagulation. Should be considered where turbidity often exceeds 5NTU or alum dose is more than 1.2 mg/l as Al.

Performance

Typically removes 90% of floc. A floc blanket clarifier can deliver a water with a colour of less than 5^{o}H and turbidity less than 5NTU.

Disturbed by

Wind. Floc blanket can be disturbed by rapid changes in flow of >10%.

Response to variable quality of input

Not affected within design limits.

Cost of ownership

High

4.9. Rapid filtration

Function

Removal of floc or particulate solids.

Description

Water flows (usually vertically down) through a bed of sand of about 1mm particle size; floc and/or suspended solids attach to sand grains in the depth of the bed. After some time the accumulation of solids causes reduction of flow or filtrate quality; the flow is stopped and the bed is cleaned by an upwash of water. The bed may be open to inspection in a rapid gravity filter or, where it is required to maintain pressure from a high-level source, enclosed in a shell or pressure filter. Means of upwash and sludge disposal are required.

Applications - actual, preferred

Few gravity filters exist on small supplies, but pressure filters are used before disinfection on some flashy stream sources and also on groundwater sources where the water is aerated to release iron. Rapid filters are also used on large works before slow filtration.

Necessary where coagulation is used, may be considered for use without coagulation where the raw water turbidity is consistently more than 4 NTU and frequently more than 10 NTU.

Performance

Up to 99% removal of turbidity and bacteria with coagulation, 50-80% without coagulation.

Disturbed by

Incorrect operation, for example excessive or inadequate backwash flow. Persistently late backwashing can cause fouling of sand.

Response to variable quality of input

With coagulation, output is stable. Without coagulation, turbidity variations are transmitted on a reduced scale.

Alternative processes

As treatment between coagulation and disinfection, there is no alternative of comparable cost. As preparation for slow filtration, plain sedimentation and gravel filtration (above) are simpler and cheaper.

Cost of ownership

Relatively high.

4.10. Slow filtration

Function

To remove moderate loads of turbidity and bacteria before disinfection.

Description

Water flows (usually down) through a bed of sand of about 0.25mm particle size. Silt accumulates on the surface to form a very fine filter layer where most of the solids are removed. This "schmutzdecke", and the sand for a few centimetres below, develops a biological coating so that the filtered water is delivered substantially free of BOD and pathogenic bacteria. While suspended colour is removed, dissolved colour is largely unaffected.

When the filter becomes blocked a 15-25mm layer is scraped off the top, leaving enough biomass to maintain performance while a new skin develops. Means required to dispose of dirty sand or washings.

Applications - actual, preferred

Normally found only on large works, most advantageous on lowland sources. There are some tens of slow filters to an upflow design on small burn supplies in Highlands and other Scottish Regions. On these upland supplies where turbidity and bacterial numbers are low, it can take a considerable time for the full bacterial action to develop.

Performance

95% removal of coliform bacteria and filtration to less than 1NTU are possible with downflow filters on lowland supplies. The upflow filter was originally intended only to remove excessive turbidity and its performance has not been fully evaluated.

Disturbed by

Raw water turbidity frequently over 10NTU causes short runs. Bacterial action will deplete dissolved oxygen and the filtered water should be reaerated by, for example, flowing over a well-ventilated weir.

Response to variable quality of input

Unperturbed.

Alternative processes

Only coagulation achieves comparable removals.

Cost of ownership

Moderate; the revenue component is low.

4.11. Carbon treatment

Function

Removes natural and synthetic organic compounds by adsorption, including any formed in treatment. Also removes free chlorine.

Description

Water to be treated passes through a contact bed either added as a layer in a filter or in a special contact vessel.

Applications - actual, preferred

Used for taste and odour control. Not in general use for small supplies except occasionally where a well has been contaminated with hydrocarbons. Has also been used to remove excess free chlorine after superchlorination.

Will find occasional application on small supplies where trace organics are present in raw waters. Normal levels of treatment have no significant effect on organic colour.

Performance

Tests are required to establish best type of carbon and contact time required. Bed life normally several months.

Disturbed by

Physical fouling, biomass development.

Response to variable quality of input

Not affected within design limits.

Alternative processes

Possibly intense chemical oxidation.

Cost of ownership

Low where carbon can be put into existing structure, but relatively high if special provision has to be made.

4.12. Chlorination

Function

Disinfection; the inactivation of bacteria and viruses, chemical oxidation.

Description

Chlorine is added to water as weak aqueous solution of either chlorine itself or sodium hypochlorite. A minimum exposure must be exceeded, expressed as residual free chlorine concentration existing at some given time after dosing. For many small supplies of high quality this is the only treatment; for others it is preceded by filtration and occasionally by chemical treatment. While it persists, the available chlorine remaining after treatment protects the water from subsequent infection.

Very large doses of chlorine will bleach out organic colour, but it is not used for this purpose.

Applications - actual, preferred

Chlorination is by far the most common method of disinfection.

Performance

Capable of making a water microbiologically safe to drink.

Disturbed by

Presence of oxidisable matter in the water.

Response to variable quality of input

Poor. Concentrations below about 0.1mg/l are ineffective while towards 1mg/l, chlorine taste is perceptible. Natural variations in chemical chlorine demand of surface waters can exceed this range many-fold. In such cases automatic equipment or sufficiently frequent adjustment of dose are needed to maintain the required exposure.

Alternative processes

Superchlorination/dechlorination, ultraviolet disinfection (below).

Cost of ownership

Can be very low for a simple system.

4.13. Superchlorination/dechlorination

Function

Disinfection; the inactivation of bacteria and viruses, chemical oxidation.

Description

Water is given a high dose of chlorine so that the exposure required for disinfection is achieved quickly and a moderate concentration remains after the chemical chlorine demand is satisfied. The residual free chlorine concentration is then lowered to a suitable low level for distribution by a chemical such as sodium sulphite or by the catalytic action of activated carbon.

Applications - actual, preferred

Not much used on small supplies, finds application where contact time is limited or where superchlorination helps reduce taste and odour.

Performance

Capable of making a water microbiologically safe to drink.
Small reduction of colour.

Response to variable quality of input

Rather more flexible than simple chlorination (above), it still needs control of the dechlorinating dose to keep the final residual within range.

Alternative processes

Ultraviolet disinfection (below).

Cost of ownership

Moderate.

4.14. Chloramination

Function

Disinfection; the inactivation of bacteria and viruses.

Description

Water is dosed with chlorine and ammonia (or on small supplies perhaps sodium hypochlorite and ammonium sulphate) in proportions such as to form monochloramine. Chlorine is dosed first so that as the ammonia is added, it predominates in local concentrations so avoiding formation of dichloramine or the noxious nitrogen trichloride.

Chlorine in this combined form is a less powerful disinfectant, but it persists for longer and allows larger chlorine doses to be used without raising complaints of chlorine tastes.

Ammonium sulphate can be dosed after superchlorination to reduce free chlorine residual without dechlorinating.

Applications - actual, preferred

Not much used on small supplies except where it is successful in reducing taste and odour.

Performance

Capable of making a water microbiologically safe to drink.

Response to variable quality of input

Rather more flexible than simple chlorination (above), it still needs control of dosage to keep the final residual within range and components in proportion.

Alternative processes

Ultraviolet disinfection (below).

Cost of ownership

Moderate.

4.15. Contact

Function

To keep water flow under control so that all elements are exposed to treatment for the same length of time.

Description

Water flowing into a contact tank or contact main is distributed evenly over the cross-section of flow. The flow area is small enough to maintain turbulent conditions and the volume is large enough to maintain the required process time. Longitudinal mixing is avoided by changing direction of flow as little as possible.

Applications - actual, preferred

A properly designed contact system is required for every chlorinated supply. In some cases the existing plant may prove to be satisfactory.

Performance

There is no generally accepted measure of performance for a contact tank. WRc has proposed a criterion based on 95% of the flow remaining in the tank for the required contact time.

Disturbed by

Changes in flow rate or volume of water in process.

Cost of ownership

Low

4.16. Ultraviolet disinfection

Function

Disinfection; the inactivation of bacteria and viruses,

Description

Water passes through a transparent tube in a closed vessel where it is irradiated with ultraviolet light. Bacteria and viruses given sufficient exposure are inactivated. The treated water carries no residual effect.

Applications - actual, preferred

Used on some scale on private drinking water supplies and (for example) on shipboard, there are about two dozen installations on public water supplies.

Because it requires an electrical supply and leaves no residual effect it is most convenient where a compact community is served from a distant source and the disinfection is applied immediately before the first consumer.

Performance

Capable of making a water microbiologically safe to drink. The light tubes lose effectiveness with age and are replaced at intervals.

Disturbed by

Turbidity and colour in the water treated impede the radiation.

Response to variable quality of input

A unit is sized to cope with the greatest expected flow and optical density.

Alternative processes

Chlorination, super/dechlorination (above).

Cost of ownership

Moderate.

4.17 Performance Ratings

The performance of the processes reviewed above is summarised in Table 1 below.

TABLE 1 - SUMMARY OF PERFORMANCE OF PROCESSES

	PROCESS	REMOVAL CAPACITY turbidity	colour	coli	COMMENTS
1	Storage	some	0	some	Beware eutrophic water
2	Screening				
3	Plain Sed'n	50 - 90%	0	50 - 90%	Raw water >4NTU
4	Gravel Filt'	50 - 80%	c.5%	50 - 80%	Beware oxygen depletion
5	pH dosing				
6	pH contact				Beware stagnation
7	Coagulation	99%	99%	99%+	FOR COLOUR REMOVAL
8	Sedimentation (after coag)	-> 2NTU	-> 5 H	90%	If Al dose>1.2mg/l
9i	Rapid Filt'n (plain)	50 - 80%	0	50 - 80%	Low colour water
9ii	Rapid Filt'n (after coag)	99%	99%	99%	Coloured water
10	Slow Filt'n	-> 1NTU	? 10%	95%	Beware oxygen depletion
11	Carbon				Beware bacterial development
12	Chlorination	0	0	99%+	
13	Super/dechl'	0	0	99%+	
14	Chloramine	0	0	99%+	
15	Contact				Needs considered design
16	UV Disinf'n	0	0	99%+	

4.18 Process Selection System

A simple system of process selection is given in Fig 1. It is intended to be pragmatic, and so treatment is not suggested where the water quality falls within the EC Directive MAC levels. This means that a source with a colour of 20^{o}H and turbidity of 4 NTU would receive disinfection only. The WHO guideline is based on a water presented for disinfection with a turbidity of 1 NTU or less. Therefore the scheme is designed so that where there is treatment of any kind before disinfection, the turbidity will be reduced to this standard. Indication of source type on the figure is for general guidance only.

Colour

If the raw water colour exceeds 20^{o}H, removal by coagulation is required. Alternative processes are not considered appropriate for general application to small supplies at the time of writing.

Particulates

Based on a target turbidity of 1 NTU and removal rates of 50%, 90% and 99% respectively for gravel filters, plain rapid filters and rapid filters after coagulation, application ranges are defined as shown. The related bacterial levels assume similar degrees of removal and a target maximum of 100 E.coli/100 ml for inactivation by disinfection. The leftmost rectangle in this section of the the figure suggests that in the UK it is not necessary to use such low quality sources for small supplies.

The section of the diagram relating to rapid filters indicates that all types have the same performance, and the selection for a particular duty will depend on practical considerations of size, cost and ease of operation.

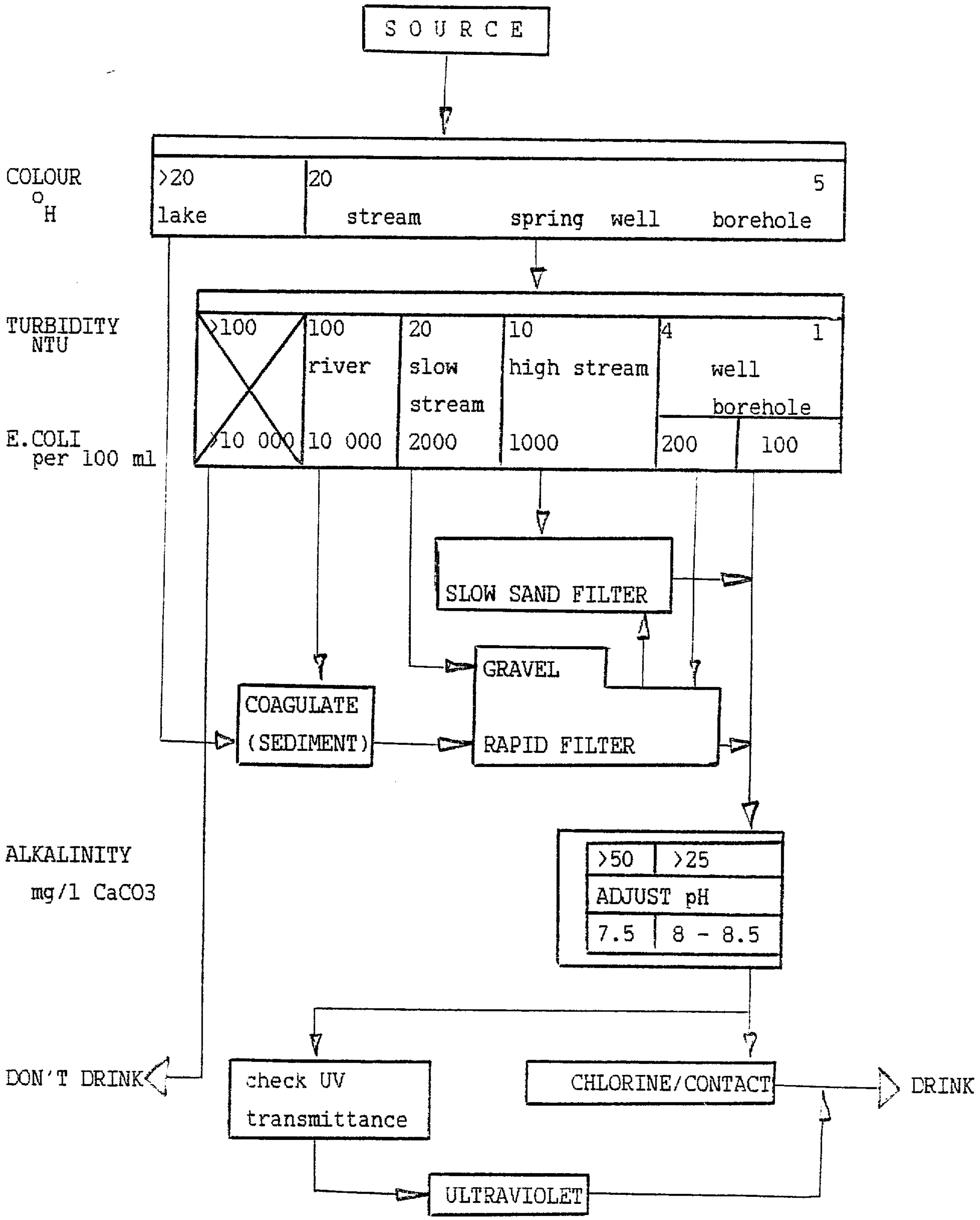
Coagulation may be followed by sedimentation if the solids load is too great for direct filtration; this may only seldom be the case for small supplies.

Alkalinity

Waters of low alkalinity benefit from pH adjustment to reduce corrosion.

Disinfection

Ultraviolet disinfection should not be adopted unless the transmittance of the water has been checked.



This chart does not take all factors into account but may be used to select preferred treatment processes for more detailed consideration.

Fig 1. TREATMENT PROCESS SELECTION SYSTEM

5. DISCUSSION

5.1 Defining the Design Raw Water Quality

The process selection system described above requires a knowledge of raw water quality. For most sources, certainly for surface sources, the quality of the water varies. For each parameter of quality there will be a range of variation according to the weather and season of the year. There will also be a rate of change of quality according to whether the source is, for example, a large reservoir where quality changes are gradual, or a flashy river. Careful consideration may therefore be necessary in deciding the values of the relevant raw quality parameters on which to base plant design.

Although this has been the case throughout the history of water treatment, it appears that every works has been treated individually and that a general approach to variability has not been developed. The tradition has been to oversize waterworks. A marginal oversizing of treatment units, even an additional process added relatively little to the capital cost of a major works and almost nothing to the operating costs. Once the works was built, the oversizing might go unnoticed unless there were need to increase output and then it would be taken as a benefit. However in present circumstances where ever better economic returns are sought, plant sizing is examined much more closely.

On a small supply the cost of oversizing is more noticeable and the provision of an additional process might increase the cost by 100%.

5.2 Characterising Variability

Consider the variations of turbidity in a stream source. Under dry weather conditions turbidity is low and declines slowly as the dry weather continues and flow decreases. After rainfall the flow increases and turbidity rises sharply, in a matter of hours. After a single shower the turbidity will slowly return to its initial low value. In continual wet weather turbidity will be high, but fluctuate in response to the times and severity of rainfall.

High on the catchment, turbidity will respond quickly to rainfall events, rising and falling with every shower. Lower down the catchment the same stream may show the same range of fluctuation but variations will be slower, reflecting the greater area drained and the longer time of passage of rainstorms.

The full statement of turbidity would be a continuous record for a period of at least a year, but this would contain much more information than the design engineer needs. The minimum statement would be the average turbidity over a long period, but such a simple statement may omit essential information about sustained high or low levels.

In most cases the information is not collected as a continuous record, as postulated above, but as a series of discrete sample values. The time interval between samples may not be uniform and the statistical methods used for expressing variation ignore the time element, regarding the data simply as a collection of values. Variability is then described in one of the following ways.

- Maximum, minimum and mean

A set of three figures shows the range of the data. If enough samples have been taken the reported mean ought to be the true mean, but there is always some possibility, however small, that the true extreme values occurred between samples. 'Max, min and mean' may include the data for a whole year or may be given as a set of seasonal, monthly or weekly figures.

- Mean and standard deviation

After the mean has been established, the standard deviation is calculated as the average variation of values from the mean. If the total set of values has a 'normal distribution', then about 95% of them will lie within two standard deviations of the mean.

- Percentile estimation

Advanced statistical techniques are used in the analysis of effluent quality data where regulations require 95 percentile compliance. There is not yet a standard method of estimation. Different Water Authorities make different assumptions as to what would be the distribution of values in a complete set of data (4).

5.3 How variability affects plant design

- Peak values affect the total size of plant. While in the first place plant is sized according to the volume of water to be treated, peak values of the water quality parameters are also involved in deciding clarifier and filter areas, sizes of chemical handling and dosing plant etc.
- Range of values affects decisions about turndown; if the effective working range of a unit is not able to span the whole range of variation, then multiple units will be required. This concerns chemical dosing plant and also affects major processes. One works, for instance, has the facility to bypass sedimentation when the solids loading is low, delivering coagulated water directly to the filters. There are very many works which would operate more efficiently if this facility had been built in.
- Rate of change of values has important implications for plant control. Where water quality is steady a works can operate very efficiently and simple processes can be tuned to a fine peak of performance. Variable waters may require different processes and may possibly benefit from the provision of automatic controls. The type of automatic control would be selected according to the speed of response needed.

  Rate of change is especially significant to biological processes where the activity of the biomass is related to the recent load and time is needed to respond to a change. It is also important where slow chemical reactions are involved. With such processes the rate of response is generally different according to whether the load is increasing or decreasing. It should be noted incidentally that electrochemical instruments are also affected in the same way.
- Duration and frequency of peak values affect initial plant design and decisions about capital investment. An isolated turbidity peak of a few hours duration would probably not affect direct filtered water quality although it would affect the run length. It would have no effect on a sedimentation and filtration plant. A turbidity peak lasting a day or so would not affect a works with 2-day bankside storage. However if a number of peaks came in close succession they might have some effect.

  The disturbances caused by peaks can be reduced by providing mixed raw water storage or by an automatic control system which adjusts the running of the plant to suit the water conditions. A simple treatment plant preceded by adequate raw water homogenisation is attractive, but raw water storage can be expensive and it can exacerbate algal problems. There is usually a best compromise between storage and plant flexibility.

5.4 Review

The designer does not need to know every small nuance of every variable; he is only really concerned to identify limiting conditions so that he can trim the design to match the limits. The point made here is that limits exist in factors other than instantaneous maximum load.

Table 2 below summarises the main factors of variability and how they affect decisions on plant design.

TABLE 2 EFFECTS OF LOAD VARIATION ON PLANT DESIGN

Factor of variability	Design considerations
Maximum value	*Total treatment capacity;* clarifier area filtration area sludge plant size capacity of chemical handling plant
Range of values	*Turndown;* type of clarifier number of clarifiers and filters links and bypasses number and sizing of dosers and instruments
Rate of change	*Responsiveness;* type of clarifier extent of automatic control accomodation for biological processes attenuation by storage quality change in storage
Peakiness	*Operational strategy;* when to close the intake optimum storage capacity and location how much spare operating capacity to provide provision for future change in strategy type of chemical treatment

5.5 Present design procedures

In the first place the designer sets out to provide a plant that will yield water of the required target quality at the full design rate of output when presented with the "design raw water quality".

The primary parameters of this quality are colour and turbidity. The available data is examined with the aim of identifying the highest levels that must be designed for so as to establish the required removal capacity in the treatment plant. Maximum levels will be noted and if they are not excessive in the designer's experience, or lie close to the average, they may be accepted as design levels. However if the maximum is well above the mean the designer will try to establish a design level below the maximum and provide a procedure for dealing with maxima, for example, reducing output, presettlement or closing the intake temporarily.

When a basic process selection and sizing has been made, the proposed works can be checked against the full raw water specification and refinements and modifications made.

5.6 Design rules for small supplies

These are some of the rules that have been proposed for small supplies.

- If turbidity $<$ 4 NTU, supply with disinfection only.
- If 4 NTU $<$ turbidity $<$ 10 NTU, slow filter before disinfection.
- If turbidity $>$ 10 NTU, settle or coagulate before filtration.
- If colour $>$ 20°H, coagulate & filter before disinfection.
- If treatment is between source and service reservoir, flow will be steady. A constant rate doser can only be used when the chlorine demand of the water does not vary by more than 10% from day to day. This may reasonably be expected from a bore or spring, or a water that has been prepared for disinfection by filtration.

It will be noted that these rules are very simple and take little account of variability.

5.7 Problems for the designer

- Lack of raw water data. The information presented to a designer is usually scant. In many cases sampling has not been carried out for long enough or with sufficient frequency to enable a complete picture to be obtained of the raw water and its variations. In many cases the whole of the information available is not presented in the most useful way and further enquiry has to be made.

- Lack of method for expressing variability. Although the above discussion has identified some of the important features of variability; peak values, ranges, rates of change and peakiness, they were only treated descriptively. No way has yet been developed, even where continuously recorded information is available, of expressing them quantitatively in such a way as to be useful to a designer in selecting and sizing treatment plant.

Lack of information on process performance. Although there is undoubtedly considerable knowledge about the response of processes to changing conditions, it resides in the experience of good plant operators and is not documented or even, perhaps, articulated. The normal monitoring of water treatment processes is aimed only at ensuring that the final treated water quality meets its targets. It is also usual to keep records of energy and chemical consumptions. When a works is newly commissioned its performance is studied closely to ensure that it meets its guarantees but this may be the only time when performance is related to raw water quality. The process guarantee conditions usually stipulate or assume steady state operation. A plant might be described as 'flexible' or tolerant of variations if

- it is oversized,
- it has a large buffer capacity or
- it has small buffer capacity but rapid start-up.

Even in WRc process research, performance tends to be related to steady state conditions.

6. RECOMMENDATIONS FOR FURTHER WORK

The first need is for a method of expressing variability numerically.

Such a method would be essentially pragmatic and would need to be developed in the context of process operation and system monitoring.

In the above development is is very likely that advances would also be made in understanding the response of processes to changing conditions.

The end results would be more efficient processes - better and more consistent products, lower operating and monitoring costs, lower plant capital costs. The results would not be applicable only to small water supplies but to all processes and industries where the raw material is drawn from the natural environment.

The initial steps for waterworks would be as follows.

- Identify one or two sites where data is being collected and recorded continuously or semi-continuously at the inlet to a process whose performance depends on the parameter(s) being monitored.

- Investigate how the process performance responds to changes of input and produce a mathematical model to describe it.

- Develop a method of describing the variability of the input stream such that, in combination with the performance model it is possible to predict the frequency and duration of events when the performance exceeds or falls short of a given level.

- Relate variability to the environmental conditions (weather and nature of catchment) and develop a model of variability which includes them.

- Change the process by installing extra storage or controls. Predict a new series of frequencies and durations. Test to see whether the prediction is verified.

It is not suggested that this work should necessarily be done under contract to the Department of the Environment.

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WRc Engineering
PO Box 85
Frankland Road
Blagrove, Swindon
Wilts SN5 8YR
Tel: Swindon (0793) 511711
Telex: 449541

WRc Environment
Medmenham Laboratory
Henley Road, Medmenham
PO Box 16, Marlow
Bucks SL7 2HD
Tel: Henley (0491) 571531
Telex: 848632

WRc (Headquarters)
John L van der Post Building
Henley Road, Medmenham
PO Box 16, Marlow
Bucks SL7 2HD
Tel: Henley (0491) 571531
Telex: 848632

WRc Processes
Stevenage Laboratory
Elder Way, Stevenage
Herts SG1 1TH
Tel: Stevenage (0438) 312444
Telex: 826168

WRc Scotland
Unit 16 Beta Centre
Stirling University Innovation Park
Stirling FK9 4NF
Tel: Stirling (0786) 71580

WRc inc
2655 Philmont Avenue
Huntingdon Valley
PA 19006
USA

WRc Water Bylaws Advisory Service
660 Ajax Avenue
Slough, Berks
SL1 4BG
Tel: Slough (0753) 37277
Telex: 449541

Registered Offices:

WRc Contracts
Cabletime Installations Ltd
Henley Road, Medmenham
PO Box 16, Marlow
Bucks SL7 2HD
Tel: Henley (0491) 571531
Telex: 848632