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WATER, SANITATION, ENVIRONMENT and DEVELOPMENT

Upgrading and uprating of water treatment plants

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Abstract

The paper describes how the contact flocculation-filtration and adsorption system (CFFA) can be used in a staged approach to cost-effectively upgrade existing Water Supply Treatment Works.

A case study is presented for modifications to the existing Water Treatment Works at Tokokoe and Befikrom in Ghana. The resulting upgraded plant is designed to be capable of handling a three-fold increase in throughput within the area occupied by the existing works units.

The CFFA system has been evaluated and developed from pilot through to full-scale units. Data from operational monitoring of the system modules show consistent performance at high throughputs up to three times conventional loadings, producing potable water meeting WHO and EC guideline values.

Introduction and background

The capacity of each of the two process streams in the existing water treatment works at Tokokoe and Befikrom (Ghana) is $45.5m^3h^{-1}$ ($10,000 gal.h^{-1}$). The water treatment works takes its source from impounding reservoir waters fed by the River Klemu near Tokokoe and the River Ochi Amisa, Befikrom.

The process units at the Tokokoe and Befikrom works are of a generic design called the "Cooke's Design" standardised on in the 1970s and adopted at a number of water treatment works in Ghana.

This paper describes proposed modifications at the plant which include converting the existing horizontal flow rectangular sedimentation tank to two vertical flow settling tanks and the mono-graded rapid gravity filter to an anthracite-sand or natural charcoal-sand dual media filter. The upflow clarifiers can be retrofitted with a steeply inclined settling tubes module enabling a staged increase in throughput with minimal additional expenditure without the need of extensive capital works.

The proposed modifications at the Tokokoe and Befikrom Water Works use the 'contact flocculation - filtration (CFF) process', (Quaye et. al., 1985). Modules of the CFF process have undergone full scale testing and development work (Quaye et al., 1985; Quaye, 1991). Data from operational monitoring show the process to be capable of producing water of high quality meeting EC 'Guideline Values' for potable water when operated at up to two to three times the conventional loading rates used in the design of the existing Tokokoe and Befikrom Water Works.

The specific design features and modular nature of the CFF process enables a staged approach to be adopted in the upgrading of a Water Works. The timing and scale of the necessary Water Supply investments can therefore be effected in order to achieve a cost-effective solution to water treatment process plant development and upgrade.

The timing and scale of water supply investments

The design horizon traditionally adopted, has been of the order of 25 years for Water and Wastewater Treatment Plants design, and about 50 years for sewers and pipelines design. There is the recognition now that staging offers significant cost benefits as shown by the following extract from the general report on 'Seven Urban Water Supply, Scheme in Ghana Howard Humphreys (1970).

"Treatment works lend themselves readily to staged construction in accordance with the increasing demand for water. Such staging should be adopted wherever practicable, in order to defer capital expansion as long as is possible.

The optimum cost in terms of present values is generally achieved with extensions carried out at intervals of 7 to 15 years, the shorter period applying to large works and longer period to small works."

Figure 1 shows an example of staging with no backlogs. Plant capacity to meet the projected demand at the end of the design horizon (x) is provided at the beginning of the period. Plant expansions to meet increasing demand are staged such that the full capacity is only utilised at the end of the design horizon.

Lauria (1969), questioned the rationale for the traditional use of rules-of -thumb with regards to design horizons and staging and derived an expression for the economy of scale factor, 'a' in terms of the optimal design period,'x*' and continuous discount rate 'r' which minimizes total present value cost. This expression is as shown in equation (1).

$$a = \frac{rx^*}{e^{rx^*}-1} \qquad (1)$$

Equation (1) defines the condition for the optimal design period x* for a given continuous discount rate 'r'. Unfortunately equation (1) cannot be solved explicitly for x*. Hence, given values for 'a' and 'r', one must rely on numerical methods 'to solve for x*. A cross plot of equation (1) for two discount rates is shown in Figure 2.

Examination of equation (1) reveals that x* is a function of only 'a' and 'r' and as systems exhibit greater economies of scale (ie 'a' decreases), the optimal design period increases. As 'r' increases (as in most developing countries), x* decreases.

Equation (1) provides a basis for determining the optimal design period for a given economy of scale and discount rate.

Economics-of-scale parameter 'a' and model scale factor 'n'

The scale factor of a model is defined as the ratio between any significant length in the prototype to its homologous length in the model. In an earlier work, Quaye (1976) assumed that the scale factor 'n' for the designed throughput of a $190m^3h^{-1}$ prototype is equal to ten times the economy of scale factor (ie for a= 0.65, n=6.5). Knowledge of the dimensions and the scale factor of the prototype facilitated the design of a pilot-scale polyzonal upflow clarifier model ($1.76m^3h^{-1}$).

This technique was used in the art of similitude to predict the scale factor of n=4 when the economy of scale factor, a=0.4. This scale factor was used in the conversion of the horizontal flow rectangular settling tanks at Tokokoe and Befikrom to two vertical flow settling tanks of $56m^3h^{-1}$ throughput per tank.

In the design of the square 45° pyramidal upflow clarifiers, the $56m^3h^{-1}$ throughput of each upflow clarifier was increased to $112m^3h^{-1}$ by retrofitting a steeply inclined settling tubes module in the clarification zone and thereby eliminating the capital expenditure to be incurred in doubling the size of water treatment plant at the end of the optimal design period when the demand equals expansion for no back-logging.

The heuristic assumption that the scale factor of a model 'n' is ten times the economy of scale factor 'a' was used to compute potential optimal cycle times, 'x*' for given continuous discount rates, 'r' as shown in Table 1.

The flexibility of the approach means that at the Tokokoe and Befikrom water works, initial improvements in operational reliability can be achieved by implementing the proposed modifications to the existing sedimentation units. Subsequent process plant upgrading and uprating can be staged through the incorporation of the settling tubes and the conversion of the mono-graded filter to a dual-media filter unit.

Contact flocculation-filtration and adsorption process

Recent work replacing the anthracite with natural charcoal has demonstrated the feasibility of adapting the design of the CFF process to a Contact Flocculation-Filtration and Adsorption (CFFA) system. The natural charcoal on top of sand facilitates the adsorption of dissolved materials and the removal of micropollutants.

The high density of natural charcoal, of the order of 2600 kgm^{-3}, results in its intermixing with the sand during the backwash fluidization stages with a resultant reduction in the expanded height of the mixed media. A lower height of filter weir can therefore be accommodated in the CFFA process design.

A schematic of the CFF process is shown in Figure 3. A CFF water treatment plant has been tested at the Morehall filter station, Sheffield (Yorkshire Water Services). Optimal upflow wash rates at various temperatures for summer, spring and autumn, and winter respectively derived from earlier work (Quaye, 1987) were used to backwash the dual-media filter bed with *water only* during the investigation.

The results of the investigation met the World Health Organisation (WHO) standards and 'EC Guideline Values' for potable water.

Water sources in Ghana

In Ghana, surface water quality impairment results mainly from soil erosion caused by heavy rains and the high incidence of water-borne diseases (eg. guinea worm, bilharzia and onchocerciasis) in a number of main rivers and streams. Surface water sources therefore usually require full treatment processes to render the water potable.

Ghana is underlain mostly by water bearing rocks with high yielding rocks found in the western, upper, eastern and southern parts of the country. Groundwater is generally of acceptable quality requiring disinfection only in most cases. Some groundwater sources in the south-western, central and south-eastern parts of the country are hard and coloured due to the presence of minerals such as calcium, iron and manganese.

Though there are usually no objectionable odour problems with both ground and surface water sources, the high iron content in some groundwater sources results in the rejection of a bacteriological safe but "dirty coloured" ground water source for an "apparently cleaner" unwholesome surface water source which might be contaminated (Andoh, 1980).

The various water sources are readily amenable to water treatment by the conventional unit processes.

Modifications to existing plant at tokokoe and befikrom works

The principal dimensions of the existing process units at the Tokokoe and Befikrom works are given in Table 2 and a schematic of the existing sedimentation unit is shown in Figure 4.

The proposed modifications to the existing process units to effect improved process reliability and increases in throughput are described for each of the unit processes.

Baffled flocculator

The baffled flocculator unit is to be retained with the spacing between the baffles modified to convert it into a tapering rapid mix unit with a rated throughput of $224m^3h^{-1}$. The estimated volume of the rapid mix unit is $2m^3$ which gives a contact time of 29 seconds for 8 baffles 760mm high. The velocity gradient is estimated to vary from about 921 to 102 s^{-1} which is within the recommended range of G (1000 - 900 s^{-1}) for rapid mixing for contact times between 20 - 30 seconds.

Sedimentation units

The sedimentation tanks of $45.5m^3h^{-1}$ throughput are to be modified to accommodate two square 45° pyramidal steeply inclined polyzonal upflow clarifiers. The features of the upflow clarifiers are highlighted in Figure 6.

Incorporating 60° settling tubes modules in the upflow clarifier results in a rated throughput of $112m^3h^{-1}$ for each upflow clarifier. The mean velocity gradient G in the upflow clarifiers ranges from $81s^{-1}$ at the bottom of the flocculation zone to $58s^{-1}$ at the top of the flocculation zone (see Figure 6). Tapering flocculation therefore continues in these units.

Figure 7 shows a schematic of the new units within the space occupied by the existing sedimentation tank. The new units occupy about 80% of the floor space of the existing units though the new units accommodate a three-fold increase in throughput. The absence of complex structures and mechanical drives reduces installation, maintenance and operating costs.

The operating characteristics of the polyzonal upflow clarifiers units are such that they can accommodate wide fluctuations in throughput whilst absorbing instantaneous increases in flow rate.

Rapid gravity filters

The existing mono-graded rapid gravity filter is converted to a dual media filter with the following effective media sizes: natural charcoal (1.2 - 2.4 mm) and fine sand (0.5 - 1.0 mm) supported on a bed of coarse sand (1.0 - 1.18 mm) and five layer gravel packing. The underdrain system is modified into a manifold (header) and perforated laterals with orifices drilled in two rows as pairs directed downwards at angles of 45° to the vertical. This results in an even collection and distribution of wash water and minimises the risks of blockage.

The new filter which occupies an area of $9.4m^2$ (ie. 4.06m * 2.31m) is rated at a maximum filtration velocity of $15mh^{-1}$. The recommended backwashing mode is a two stage water only backwash (Quaye, 1987). The estimated washwater volume required per filter is about $84.5m^3$ for a 24 hours filter run. This results in a net outflow of 94 m^3h^{-1}. The quantity of wash water required is estimated to be less than 4 % of the total quantity of filtered water over the operating period in a day (ie. 23.5 hrs) at a mean filtration velocity of $10mh^{-1}$.

The total head loss through the new dual-media filter unit is estimated to be of the order of 6.5m. Taking account of the washwater outlet pipe location results in an additional 2.5m. A total driving head of the order of not less than 10m will therefore be required for the modified works.

A filtrate turbidity monitor is recommended to monitor the turbidity of the filtrate and to initiate automatic backwashing of the filter media.

Ancillary equipment

The other relevant components to the plant modification include the necessary chemical tanks to store and dose solutions of the coagulant, flocculant aid and pH adjusting chemicals as necessary. These are typically 500 litre polythene chemical solution side bracket mounted tanks. The dosing tanks require PVC coated electrically driven stirrers, PVC outlet terminal pipework including sight tubes for pump calibration and isolating valves. Simplex diaphragm chemical dosing pumps of about $30lh^{-1}$ capacity are recommended.

Ranges of flexible solution delivery hoses, injection fittings, base plates and a wall mounted coagulant plant control panel are also recommended.

Summary and conclusions

A contact flocculation-filtration and adsorption (CFFA) process using a dual-media filter developed from laboratory-scale apparatus and pilot-scale filter plants and a polyzonal upflow clarifier incorporating a steeply inclined settling tubes module as a flocculator, has been developed as a high rate modular water treatment process.

Incorporating modules of the CFFA process in an upgrading and uprating exercise for the existing water treatment works at Tokokoe and Befikrom has resulted in a three-fold increase in throughput. The modular nature and flexibility of the CFFA process lends it to an optimal staging approach in plant capacity increases.

References

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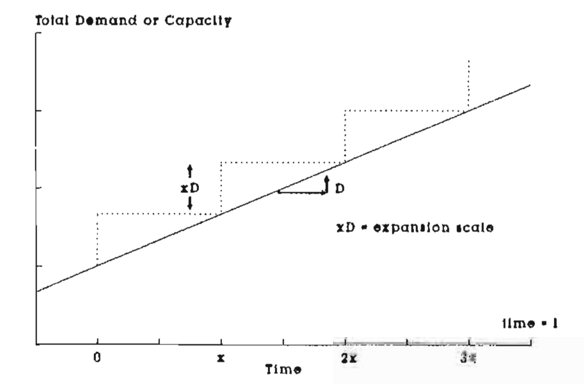
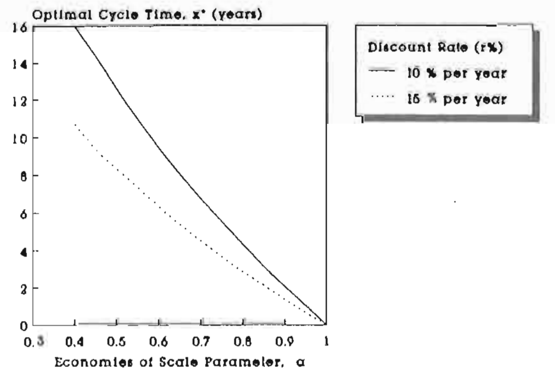


Figure 1. Demand & capacity without backlogs



(after Lauria, 1969)

Figure 2. Cross plot for optimal design period

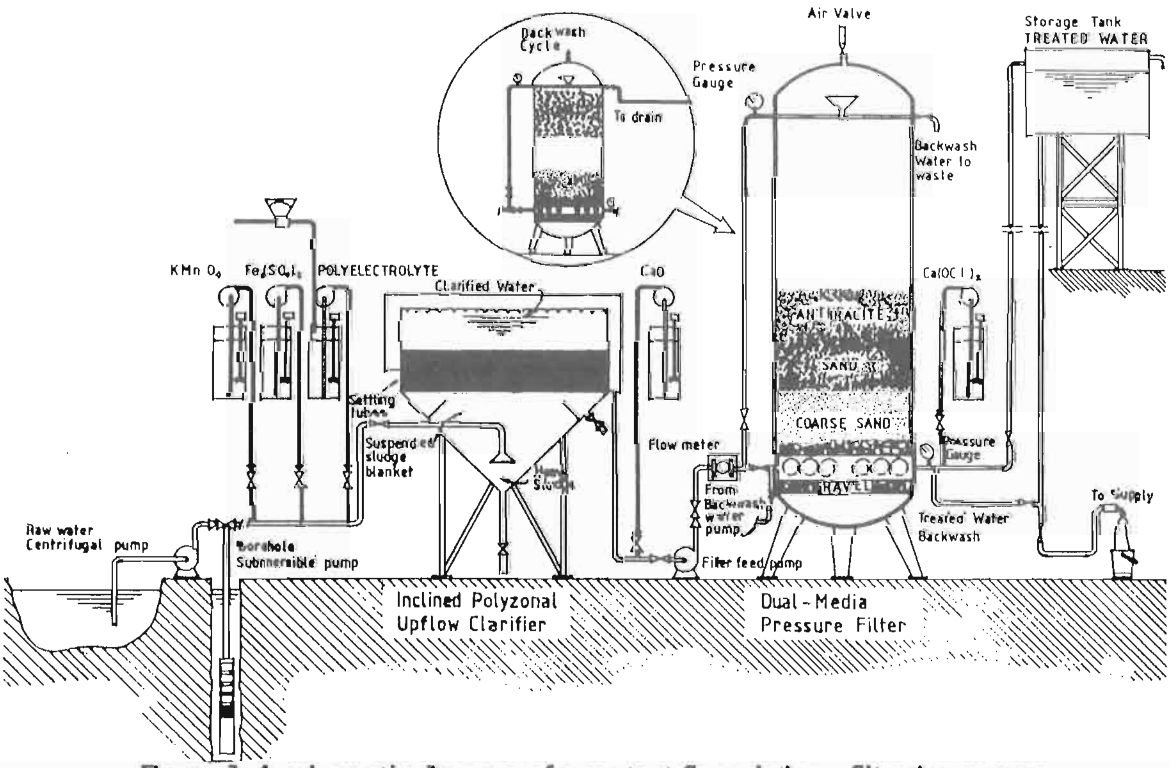


Figure 3. A schematic diagram of a contact flocculation - filtration system

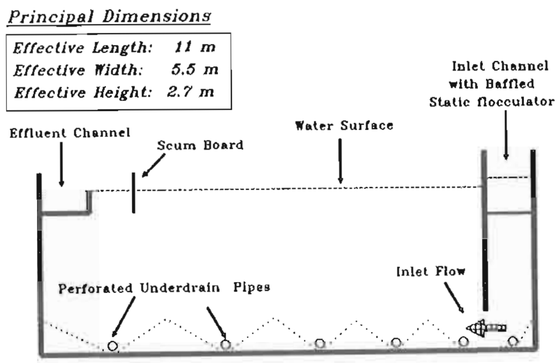


Figure 4. Horizontal flow sedimentation unit

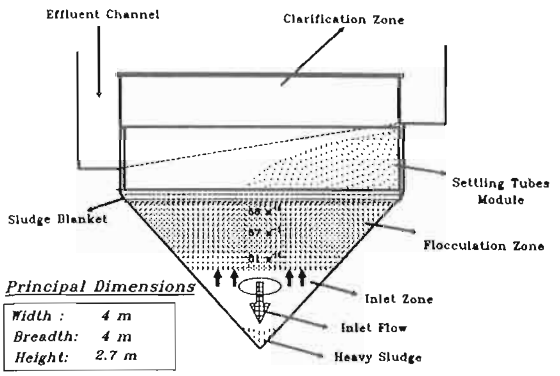


Figure 5. Inclined polyzonal upflow clarifier

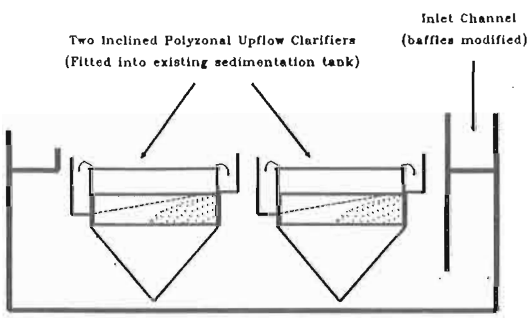


Figure 6. Modifications to sedimentation unit

Table 1. Economics of scale parameter 'a'

Economy of scale factor a	Model scale factor n	Cont discount rate r%	Optimal Cycle time in years x*
0.40	4.0	6.0	27.0
0.40	4.0	8.0	20.2
0.40	4.0	10.0	16.0
0.48	4.8	6.0	22.0
0.48	4.8	8.0	16.5

Table 2. Principal dimensions

PROCESS UNIT	LENGTH (M)	WIDTH (M)	HEIGHT (M)
Sedimentation Tank	11	5.5	2.7
Baffled Flocculation	2.72	0.91	0.76
Sand Filter	4.06	2.31	2.7