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Extended Plain Sedimentation

By Kuan M. Yao,[1] M. ASCE

Introduction

Pretreatment is often necessary for water treatment plants using surface sources taken from natural streams. Chemical coagulation followed by flocculation and settling is normally used in a conventional filtration plant. It is conceivable that plain sedimentation could be a possible alternative as a pretreatment process, for small communities and individual homesteads located in isolated or remote areas and for developing countries where both chemical coagulants and skilled plant operators necessary for the successful process control of coagulation are in short supply if available at all.

With the general awareness of environmental pollution, extended plain sedimentation has two factors in its favor. First, the process does not increase overall pollution. There are numerous cases where a pollution control process actually introduces more pollution into our environment as a whole. A drastic example was cited by Ling who stated that, for the removal of 1 lb of pollutants for wastewater reclamation, 4 lb of chemicals have to be added in the process (3). The second favorable factor is that sludge from plain sedimentation is much less objectionable for its disposal than that from chemical coagulation.

A number of small communities in Pakistan rely on surface water drawn from the famous Indus Valley irrigation canal system as the source for their public water supplies. In order to avoid service interruptions during annual canal cleaning, a raw water storage tank is usually incorporated into the slow sand filtration plant extensively used for water treatment. The storage capacity of the tank is about the equivalent of a 3-week supply, the duration of canal cleaning. It appears that the storage tank also provides plain sedimentation to reduce the raw water suspended solids to a level adequate for slow sand filters, even though the raw water turbidity may stay at hundreds of turbidity

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[1] World Health Organization Prof. of San. Engrg., Univ. of Engrg., and Tech., Lahore, Pakistan.

units for prolonged periods. This tends to demonstrate that extended plain sedimentation is technically feasible to serve as pretreatment in a water purification system.

Extended plain sedimentation of natural waters could also find applications in silting control of impounding reservoirs and, possibly, urban stormwater treatment.

The purposes of the present study are to: (1) Undertake theoretical and laboratory investigations of the settling characteristics of suspended particles in natural streams over extended periods without coagulation; and (2) examine the various practical aspects in using extended plain sedimentation as a water pretreatment process.

Raw water taken from a nearby irrigation canal was used in the study. Since the properties of suspended particles may vary from stream to stream, the results are valid only for the raw water used. However, it is hoped that the results obtained may serve as a general indication of the performance of extended plain sedimentation in the treatment of natural surface waters.

Theoretical Considerations

Suspended particles in natural streams are mainly silt, clay and, possibly, fine sand, with sizes ranging from submicron to tens or even hundreds of microns ($1\ \mu = 10^{-4}$cm). Apart from advection due to fluid flow, the most important particle transport mechanisms in plain sedimentation are gravitational settling and diffusion. The relative significance of the two mechanisms to a given suspended particle depends largely on its size. Diffusion can be dominating when the particle size becomes small.

It can be shown that the ratio of the displacement of a suspended particle in a given time period due to diffusion to that due to gravitational settling is as follows (5,6):

$$\frac{x_d}{x_g} = \frac{8.29}{\gamma_s - \gamma}\left(\frac{kT\mu}{t}\right)^{0.5}\frac{1}{d^{2.5}} \quad \text{(1)}$$

in which x_d and x_g = displacements of the suspended particle during time t due to diffusion and gravitational settling, respectively; γ_s and γ = specific gravities of the suspended particle and water, respectively; k = Boltzmann constant; T = absolute temperature; μ = dynamic viscosity of water; and d = particle diameter. Since the two mechanisms act on the particle concurrently and simultaneously, Eq. 1 is not physically valid and indicates only the relative order of magnitude of x_d and x_g.

Fig. 1 is the plot of Eq. 1 for different values of t, using water temperature = 20° C, $\mu = 1.01 \times 10^{-2}$ g-mass/cm-s, $k = 1.38 \times 10^{-16}$ erg/ °K, $\gamma_s = 2.65$ g/cm^3, and $\gamma = 1$ g/cm^3. Fig. 1 indicates that the relative significance of the two mechanisms varies with particle size as well as the settling period. The longer the period, the less pronounced will be the diffusion effect for a given particle size. This is probably due to the random nature of the Brownian movement as compared with the unidirectional gravitational settling. The time factor tends to become insignificant when the settling period is longer than 5 days. This may mean that in extended plain sedimentation, the settling characteristics of suspended particles will not be unduly affected by varying settling periods. As expected, the effect of diffusion decreases rapidly with the increase of particle size. If a difference of two orders of magnitude or more between x_d and x_g is considered to be sufficient to ignore the significance of the lesser one, the limiting particle sizes with gravitational settling dominating will be about 1.4 μ for $t = 1$ hr, 0.5 μ for $t = 5$ days, and 0.4 μ for $t = 20$ days. These sizes are in general agreement with the upper limit of the so-called colloidal particles. These same figures also indicate the practical limit of the removal of suspended particles that can be attained by gravitational settling.

Stokes law is normally used to describe gravitational settling of discrete particles and is as follows (5):

$$U = \frac{1}{18}\frac{d^2}{\mu}(\gamma_s - \gamma) \quad (2)$$

in which U = settling velocity of a suspended particle. The design parameter

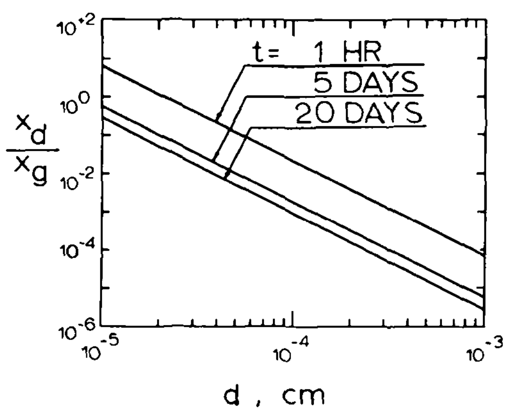

FIG. 1.—Relative Significance of Diffusion and Gravitational Settling for Different Particle Sizes

overflow rate is actually another form of the settling velocity and can be obtained readily from the latter by applying an appropriate unit conversion factor (1).

Since the viscosity of water decreases with the increase of temperature, Eq. 2 indicates that a higher design overflow rate may be employed at higher temperatures for the removal of suspended particles of a given size. For instance, if the feasible lower limit of particle size for removal by plain sedimentation is taken as 1 μ, the corresponding design overflow rates will be around 2 gal/day/sq ft (0.08 m/day) at 20° C and 2.5 gal/day/sq ft (0.10 m/day) at 28° C. This seemingly small difference in overflow rate actually means that the total tank area required in the latter is 25% less than that for the former. This situation is further accentuated by the fact that, as shown in Eq. 1, the effect of diffusion tends to be more pronounced at low temperatures, making gravitational settling less effective. Thus, a much more thorough study of the suitability of extended plain sedimentation should be made before its application in cold regions.

It has been generally recognized that detention time is not a major factor in settling tank design. Consider, for instance, the design limit of 2 gal/day/sq ft (0.08 m/day) for plain sedimentation mentioned previously. The corresponding detention time will be 740 hr if the water depth is 8 ft (2.4 m), 900 hr if the water depth is 10 ft (3 m), or 1,040 hr if the water depth is 14 ft (4.3 m). It is easy to see that a deeper tank merely increases the detention time without achieving functional improvements. This, in fact, illustrates the basic difference between a tank designed for storing water and a tank designed for settling. Thus, to be more appropriate, the term extended plain sedimentation should be interpreted as extension towards a lower design overflow rate as compared with those used in conventional plants rather than as extension in detention time.

Experimental Study

The experimental study was conducted in the form of quiescent settling in a settling column on a batch basis. The settling column, which is approx 15 cm in internal diameter and 93 cm in height, was made from transparent perspex sheets. A sampling port was located at a distance of 5.5 cm from the bottom of the column. The port was covered with a rubber membrane. A hypodermic syringe fitted with a long needle was used to withdraw samples through the port. The needle was of sufficient length to draw samples near the central portion of the column.

Raw water was brought from the main irrigation canal about 3 miles (4.8 km) from the laboratory. The canal was fed by one of the tributaries of the Indus River without the provision of a reservoir. No significant industrial or municipal sources of pollution were known to exist on the upstream of the intake of irrigation water. Some pollution was introduced by the buffalos bathing in some stretches of the canal. The water was fairly turbid in the summer and became somewhat clearer later in autumn. Fresh raw water was taken on the day an experimental run was to be made.

For each experimental run, the settling column was filled to a marked level of 83.5 cm from the bottom. Zero time was set as soon as the filling was complete. A uniform turbidity or suspended solid concentration was assumed at time zero in view of the violent agitation created during filling. The column was situated in a corner of the laboratory away from sunlight and movements of laboratory staff and was covered with a thick book to minimize outside disturbances. The following general sampling schedule was followed with zero time as the baseline: 1 hr, 2 hr, 3 hr, 24 hr, 48 hr, 72 hr, 96 hr, and 120 hr (5 days). However, some runs were extended far beyond the fifth day and one run was terminated at the end of the second day when the residual turbidity reached an exceptionally low level.

In addition to the sample withdrawn through the sampling port, a second sample was taken at the water surface of the settling column at each sampling time. The residual turbidity of the surface sample was considered as an indication of the best obtainable result for the corresponding settling period.

Water temperature was measured at the time raw water was taken from the canal and at each sampling time during a run. The water temperature varied from 24° C-31° C. However, the variation of temperature for each run tended to be within a relatively narrow range of 3° C–4° C. No attempt was made to maintain a constant water temperature.

Turbidity was used as the main indicator of settling performance. Suspended solids concentrations were also determined for raw and final settled water as well as for some intermediate samples. The main reason for not measuring suspended solids concentration for every sample was the relatively large volume required for its determination. This could result in large fluctuations of water level in the column during a run. In one case, a sample volume of 500 ml was necessary to obtain significant results. The total volume of water filled to the marked level of the settling column was 16 l.

A Hach Laboratory Turbidimeter, Model 2001A, was used for turbidity measurements. The result was expressed in Formazin turbidity unit (Ftu) which is the equivalent of the Jackson turbidity unit (Jtu). For suspended solids concentrations, a standard method procedure was followed using glass fiber filters (4).

Altogether five runs, identified in chronological order as Runs 1, 2, 3, 4, and 5, were made. The raw water turbidities for the runs were 225 Ftu, 225 Ftu, 250 Ftu, 125 Ftu, and 77 Ftu, respectively.

It was observed that, after the initial period of a few hours, the turbidity in the settling column tended to approach a uniform state throughout its depth. The turbidity of the sample taken at the sampling port was always within 10% of that measured at the water surface when the settling time was 24 hr or longer. This is in contrast with examples on settling experiments presented in many textbooks.

Analysis of Experimental Results

Settling Efficiency Obtainable by Plain Sedimentation.—It has been shown herein that gravitational effect dominates the settling of natural suspended particles down to the size of about 1 μ. Since water in natural streams may contain particles of submicron sizes, it is therefore not practical to rely on plain sedimentation for the complete removal of suspended particles from natural waters. It is also conceivable that, even for particles with sizes above 1 μ, their removal in practice will not follow completely the theoretical predictions. On the other hand, some submicron particles may be removed in a gravitational settling device since diffusion is not always working against gravity. Thus, theoretical investigations tend to yield results of qualitative nature and experimental settling studies are often indispensable in providing the essential information for practical design of settling tanks.

One part of the experimental study was to investigate the settling efficiency that can be achieved by plain sedimentation within reasonable settling periods. This was made by measuring the turbidities of samples taken at the water surface of the settling column at various settling periods. Fig. 2 presents the relevant results. The curve in the figure represents the arithmetic average of the results from the runs indicated in the figure with the exception of Run 5 which tends to show settling characteristics very different from those of the other runs. One possible reason for this anomaly was its relatively low initial turbidity, which could indicate the beginning of the seasonal change of raw water turbidity.

The average curve in Fig. 2 indicates that rapid turbidity reduction occurs within the first 2 hr-3 hr. The rate of reduction tends to decrease with time. Approximately two-thirds of the initial turbidity is removed at the end of the first day and there is an average reduction of 80% at the end of the second day. From this point on, there is a definite trend of diminishing return for further settling time increases. The average turbidity reduction up to the end of the fifth day is approx 87%. As far as plain sedimentation is concerned,

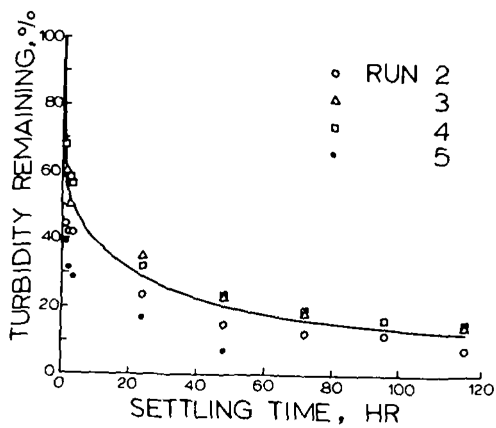

FIG. 2.—Turbidity Remaining at Different Settling Time in Samples Taken at Surface of Settling Column

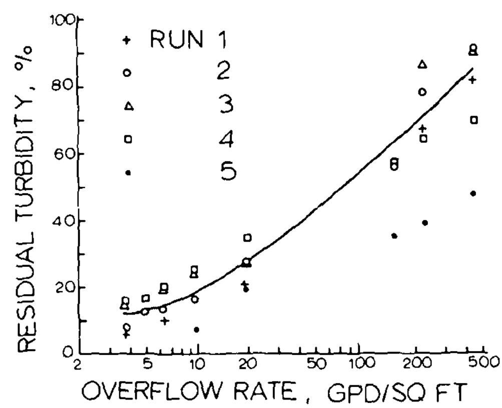

FIG. 3.—Experimental Residual Turbidity, as a percentage, at Different Overflow Rates or Settling Velocities

such performance may not be too bad. In terms of the actual residual turbidity of the settled water, the situation may be slightly different. For instance, if the initial turbidity is 250 Ftu, the residual turbidity of the settled water after a 5-day quiescent settling period will be about 37 Ftu, which appears rather high when compared with a residual turbidity of less than 10 Ftu for properly treated settled water in a conventional rapid filtration plant (2). Therefore, it was felt that it would be interesting to see whether a level of residual turbidity as low as 10 Ftu could be obtained by plain sedimentation within a reasonable settling time. Surface sampling for Run 4, therefore, was extended until a residual turbidity of 8.5 Ftu was reached at the end of the eleventh day. This tends to indicate that plain sedimentation does have the flexibility of providing an adequate range of performance without the need of unduly long settling periods. It is important to point out here that settling period refers to the time of quiescent settling and is not the same as the detention time of a settling tank.

Experimental Settling Curve.—Fig. 3 presents the experimental results based on samples taken through the sampling port of the settling column. The settling characteristics of Run 5 are again different from those of others and therefore are not considered in constructing the average settling curve in the figure. The settling velocity is expressed in its equivalent overflow rate to facilitate practical interpretations.

As indicated in Fig. 3, there is a rapid rate of turbidity reduction down to about 20 gal/day/sq ft (0.82 m/day). The rate decreases from this point on. On the average, the settling efficiencies are about 50% at 80 gal/day/sq ft (3.26 m/day), 80% at 10 gal/day/sq ft (0.41 m/day), and 85% at 6.4 gal/day/sq ft (0.26 m/day). The significant portion in extended plain sedimentation will be the lower end of the curve up to approx 20 gal/day/sq ft (0.82 m/day).

The percentage removal shown in Fig. 3 does not indicate the exact quality of the end product, which is often of vital interest in a water treatment plant. In order to investigate this aspect of settling, Runs 1 and 4 were extended beyond the fifth day until the residual turbidity fell below 10 Ftu.

Fig. 4 is the plot of the results with the residual turbidity as ordinate. It is interesting to note that the two curves tend to approach each other when the overflow rate becomes lower than 20 gal/day/sq ft (0.82 m/day) even though the initial turbidity was very different for the two runs. Fig. 4 indicates that, to obtain a residual turbidity of 10 Ftu, the required design overflow rate is about 2 gal/day/sq ft (0.08 m/day).

Interpretation of Experimental Settling Curve.—Both Figs. 3 and 4 are based on the residual turbidity measured at the sampling port at various settling periods. The residual turbidity would be different if samples were taken at points different from the sampling port. This means that Figs. 3 and 4 indicate only the performance of settling at a given level over various settling periods. In a real settling tank, the effluent of the tank will be the mixture of settled water from different levels throughout its depth rather than from a single level. Thus, there is the need to interpret the experimental results from a settling column study for practical settling tank design. One way is to apply a method of graphical integration (1). Fig. 5 presents the results obtained by this method using the average settling performance shown in Figs. 3 and 4 up to an overflow rate of 20 gal/day/sq ft (0.82 m/day). Fig. 5 presents the predicted settling tank efficiency at different design overflow rates. It has been suggested that slow sand filters can be operated economically if the filter influent turbidity is kept below 30 units (2). Assuming a maximum raw water turbidity of 250 Ftu, the required settling efficiency would be 88%. From Fig. 5, the design overflow rate should be approx 10 gal/day/sq ft (0.40 m/day). The corresponding detention time is about 180 hr (7.5 days) if the water depth of the tank is 10 ft (3 m).

Turbidity Versus Suspended Solids Concentration.—In the preceding analysis, turbidity removal has been used as the indicator of settling performance. In waters containing a wide range of particle sizes, turbidity removal may have relatively limited physical significance and suspended solids concentration would offer a better indication to express the actual amount of materials removed. Thus, suspended solids concentrations of raw and settled water samples as well as some intermediate samples were determined along with their turbidities. Fig. 6 is the plot of the results indicating the empirical correlation between

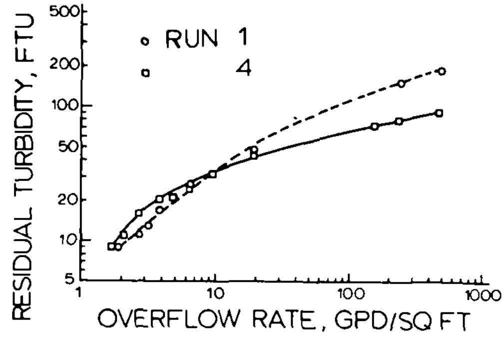

FIG. 4.—Experimental Residual Turbidity, in Ftu, at Different Overflow Rates or Settling Velocities for Runs 1 and 4

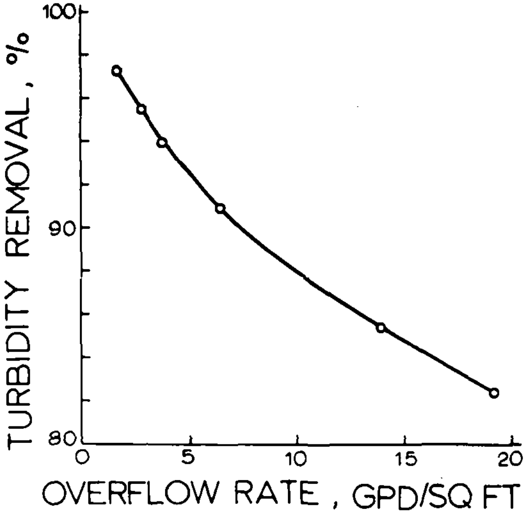

FIG. 5.—Experimental Settling Tank Performance Curve

the two parameters for the water used in the study. Generally speaking, the suspended solids concentration, in milligrams per liter, tends to be two or three times greater in magnitude than the turbidity, in Formazin turbidity units, when the turbidity of water is in hundreds of units. The relationship is reversed with the magnitude of turbidity on the high side when the turbidity is relatively low. The turning point appears to be at the point of 100 units for both parameters.

Strictly speaking, turbidity and suspended solids concentration measure two different quantities in natural waters. Suspended solids determinations do not include submicron particles which may play an important role in causing the turbidity of water, especially in the latter stage of a settling experiment when most of the larger suspended particles have been removed. Fig. 6 is probably valid only for the raw water studied. However, the general pattern could be similar for other raw waters.

Fig. 6 tends to cast a new light on the experimental results. For instance, consider a raw water with an initial turbidity of 200 Ftu and a turbidity removal efficiency of 85%. The settled water would have a residual turbidity of 30 Ftu. From Fig. 6, the corresponding suspended solids concentrations for the raw and settled water are 600 mg/l and 20 mg/l, respectively. Thus, in terms of suspended solids removal, the system efficiency will be about 97%.

The types of results presented herein can also be used for predicting the performance of a given tank design. Assume that a detention time of 5 days

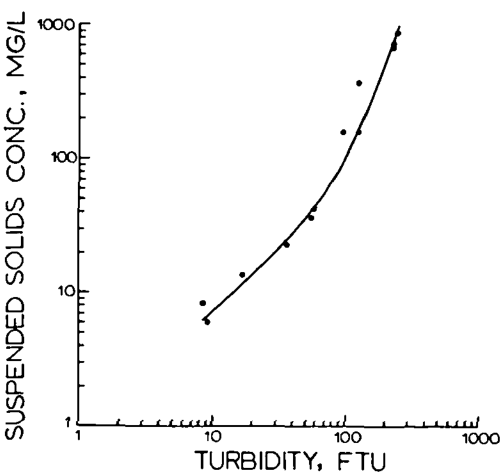

FIG. 6.—Turbidity Versus Suspended Solids Concentration

is provided in settling tanks of 10-ft (3-m) depth with a maximum raw water turbidity of 250 Ftu. By the use of Figs. 5 and 6, the estimated relevant values are: design overflow rate = 15 gal/day/sq ft (0.61 m/day); turbidity removal efficiency = 85.4%; residual turbidity of settled water = 36 Ftu; and residual suspended solids concentration of settled water = mg/l.

Practical Considerations

The overall effect of the long detention time required in extended plain sedimentation on water quality is not known. Nothing was observed during the experiments to indicate any such effect. Presumably, the effect, if any, will vary depending on the nature of the raw water. Algal growth could be a problem under favorable conditions for such growth.

The suspended solids remaining in the settled water will no doubt include submicron particles which may not be easily removed by rapid filters without some kind of chemical treatment. On the other hand, slow sand filters could be effective in removing these particles, especially after the surface layer has been properly built up.

It is conceivable that, in some cases, the relatively large land area needed for extended plain sedimentation is either not available or too expensive. Tube settling may offer a possible alternative. Further studies are needed since most previous studies on tube settling dealt with coagulated water (7).

The construction cost for providing the large settling volume could be substantial. One way in getting around this is to use techniques such as earthen ponds with plastic or rubber lining.

The operating cost of these large settling tanks could be expensive if automatic sludge removal is used. Hopper bottom construction may increase the construction cost substantially. Manual cleaning is probably the choice in places where unskilled labor is reasonably cheap and the frequency of cleaning is small. Manual cleaning is especially suitable in cases where raw water becomes fairly clear in a certain period of the year to allow the settling tank to be emptied for cleaning without affecting the production of the plant. Otherwise, extra capacity is necessary as standby for tank cleaning.

Summary and Conclusions

The theoretical lower limit of the design loading for extended plain sedimentation with gravitation as the dominating transport mechanism is about 2 gal/day/sq ft (0.08 m/day) corresponding to a detention time of 38 days in a 10-ft (3-m) settling tank if the water temperature is 20° C.

Experimental results indicate that plain sedimentation is technically feasible to reduce a substantial amount of turbidity of natural waters. A residual turbidity lower than 10 Ftu can be obtained if reasonable setting time is provided.

Based on the results of the settling study, a design overflow rate of 10 gal/day/sq ft (0.40 m/day) is required to bring turbidity down to the economical level for slow sand filtration. The corresponding detention time is 7.5 days, provided that the water depth of the settling tank is 10 ft (3 m).

Suspended solids concentration appears to be more appropriate for assessing the performance of extended plain sedimentation of natural waters as a pretreatment process. In terms of solid mass removal, an 85% turbidity reduction actually indicates a suspended solids removal of 97%.

From the viewpoint of the functioning of settling tanks, extended plain sedimentation should be interpreted as an extension towards a lower design overflow rate rather than an extension towards a longer detention time.

Some considerations are presented in the application of extended plain sedimentation for practical uses.

Acknowledgments

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Appendix II.—Notation

The following symbols are used in this paper:

d = diameter of suspended particle;
k = Boltzmann constant;
T = absolute temperature;
t = period of quiescent settling;
U = settling velocity of suspended particle;
x_d = distance traveled by particle due to diffusion;
x_g = distance traveled by particle due to gravitational settling;
γ = specific weight of water;
γ_s = specific weight of suspended particles; and
μ = dynamic viscosity of water.

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KEY WORDS: Design; **Environmental engineering; Sedimentation;** Settling basins; **Suspended solids; Water treatment**

ABSTRACT: Extended plain sedimentation could be a possible alternative for pretreatment of surface waters in water purification. It does not add pollution to the environment and its sludge is less objectionable for disposal. Theoretical investigation shows that gravitational effect dominates settling down to the particle size of 1 μ. Experimental results indicate that extended plain sedimentation is technically feasible to remove a substantial amount of turbidity with residual turbidity down to less than 10 FTU. An 88% turbidity removal could be achieved in a settling tank of 7.5-day detention. Suspended solids concentration appears to be more appropriate as an indicator of the performance of settling of natural waters. From the viewpoint of functioning of settling tanks, extended plain sedimentation should mean extension towards a lower design overflow rate rather than towards longer detention periods.

REFERENCE: Yao, Kuan M., "Extended Plain Sedimentation," *Journal of the Environmental Engineering Division*, ASCE, Vol. 101, No. EE3, **Proc. Paper 11392**, June, 1975, pp. 413-423