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Opportunities, Needs and Strategic Direction for Research on Flocculation in Natural and Engineered Systems

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Opportunities, Needs and Strategic Direction for Research on Flocculation in Natural and Engineered Systems

Ian G. Droppo, Gary G. Leppard, Steven N. Liss and Timothy G. Milligan

Abstract

In the history of environmental science, there has probably been no greater struggle than the attempt to control the impact of the sediment and solids generated by nature and human influence (including industrial processing) on the terrestrial and aquatic environments and on socioeconomics in general. Flocculation is a process inherent within both natural and engineered systems such as wastewater treatment and is simply the aggregating of smaller particles together to form larger composite particles via various physical, chemical and biological interactions. These larger composite particles behave differently in terms of their physical (e.g. transport, settling), chemical (e.g. contaminant uptake and transformation), and biological (e.g. community structure activities and metabolism) behaviour relative to their constituent individual particles due to differences in size, shape, porosity, density and compositional characteristics. Given these significant behavioural differences between flocs *per se* and their individual component parts, flocculation influences a wide array of environmental phenomena related to sediment-water and sediment-sediment interactions. A few of these include sediment and contaminant transport in various aquatic ecosystems, remediation of contaminated bed sediments, contaminated bed sediment stability, and habitat destruction resulting from sedimentation (e.g. coral reefs, salmon spawning reds, mollusk habitat degradation). These concerns, coupled with the ubiquitous nature of flocs within natural and engineered systems and the potential to influence floc properties to better control environmental and engineered processes, have generated an increased emphasis on floc research. This chapter summarizes the outcomes of a workshop entitled "Flocculation in Natural and Engineered Environmental Systems" and provides a perspective on the unifying principles of flocculation between saltwater, freshwater and engineered systems.

NWRI RESEARCH SUMMARY

Plain language title

Opportunities, Needs and Strategic Direction for Research on Flocculation in Natural and Engineered Systems.

What is the problem and what do scientists already know about it?

Flocculation plays an essential role in mediating the physical, chemical and biological properties of not only the sediment itself, but also of the aquatic or engineered system as a whole. As such, the flocculation process has significant environmental and socioeconomic implications. For example, flocculation plays an important role in sediment and associated contaminant fate and effect, reduces reservoir capacity and fisheries habitat due to increased sedimentation, is used as a remediation strategy for oil spills and toxic algal blooms, and dictates the efficiency of wastewater treatment systems. While untold billions of dollars are spent each year on issues for which flocculation is the key process, our understanding of the underlying mechanisms is still developing.

Why did NWRI do this study?

This paper represents the concluding chapter for a book entitled "Flocculation in Natural and Engineered Environmental Systems". It provides a perspective on the unifying principles of flocculation from the freshwater, saltwater and engineered systems derived from the 19 proceeding chapters and from discussion with all participants during breakout ad plenary sessions. This book will provide a strong contribution to furthering our understanding of flocculation in multiple environments.

What were the results?

The results stated in this chapter are a synopsis of the entire book and discussions derived from the workshop as a whole. The chapter provides information on the unifying principles of flocculation, challenges and emerging issues in flocculation research.

How will these results be used?

The chapter will appear within the book "Flocculation in Natural and Engineered Environmental Systems" and will provide users with both scientific and practal understanding of floc related issues within multiple environments.

Who were our main partners in the study?

This study is done in partnership with Ryerson University and The Bedford Institute of Oceanography, Department of Fisheries and Oceans.

Possibilités, besoins et orientations stratégiques de la recherche sur la floculation dans des systèmes naturels et artificiels

Ian G. Droppo, Gary G. Leppard, Steven N. Liss et Timothy G. Milligan

Résumé

Dans l'histoire des sciences de l'environnement, il n'y a probablement pas eu de plus grande lutte que celle visant l'élimination de l'effet des sédiments et des solides générés par la nature et par l'action des humains (y compris la transformation industrielle) sur les milieux terrestres et aquatiques et sur les conditions socio-économiques en général. La floculation est un processus inhérent à des systèmes naturels et artificiels, comme les systèmes d'épuration des eaux usées, et consiste simplement en l'agrégation de petites particules formant de plus grandes particules composites au moyen de diverses interactions physiques, chimiques et biologiques. Sur le plan des propriétés physiques (p. ex., transport, sédimentation), chimiques (p. ex., assimilation et transformation de contaminants) et biologiques (p. ex., activité des communautés et métabolisme), ces particules composites de plus grande taille diffèrent par rapport à leurs constituantes, les particules individuelles, à cause de différences de taille, de forme, de porosité, de densité et de composition. Étant donné ces importantes différences entre les flocs en tant que tels et chacune de leurs composantes, la floculation agit sur un grand éventail de phénomènes environnementaux liés aux interactions sédiment-eau et sédiment-sédiment. Le transport des sédiments et des contaminants dans divers écosystèmes aquatiques, la restauration et la stabilisation des sédiments contaminés du lit des cours d'eau et la destruction de l'habitat résultant de la sédimentation (p. ex., la dégradation des récifs de corail, des lieux de frai du saumon et de l'habitat des mollusques) sont quelques-uns de ces phénomènes. Ces préoccupations, ajoutées à la nature ubiquiste des flocs dans les systèmes naturels et artificiels et à la possibilité qu'on a d'agir sur les propriétés des flocs afin de mieux maîtriser les processus environnementaux et artificiels, ont accru l'intérêt pour la recherche sur les flocs. Le présent chapitre est un résumé des résultats d'un atelier intitulé « Flocculation in Natural and Engineered Environmental Systems » et offre un point de vue sur les principes de la floculation applicables aux systèmes salins, dulcicoles et artificiels.

Sommaire des recherches de l'INRE

Titre en langage clair

Possibilités, besoins et orientations stratégiques de la recherche sur la floculation dans des systèmes naturels et artificiels.

Quel est le problème et que savent les chercheurs à ce sujet?

La floculation influe de façon importante sur les propriétés physiques, chimiques et biologiques, non seulement des sédiments mais aussi des systèmes aquatiques ou artificiels dans leur entier. À ce titre elle a donc des conséquences environnementales et socio-économiques importantes. Par exemple, elle joue un grand rôle dans le devenir et les effets des sédiments et des contaminants qui s'y associent, réduit la capacité des réservoirs et des habitats de pêche à cause d'une sédimentation accrue, est utilisée comme moyen de dépollution pour les déversements pétroliers et la prolifération d'algues toxiques, et détermine l'efficacité des systèmes d'épuration des eaux usées. Des milliards de dollars sont dépensés chaque année pour des activités où la floculation est le processus essentiel, mais nos connaissances sur les mécanismes sous-jacents restent à parfaire.

Pourquoi l'INRE a-t-il effectué cette étude?

Le présent article porte sur le dernier chapitre du livre intitulé « Flocculation in Natural and Engineered Environmental Systems ». Ce chapitre offre un point de vue sur les principes de la floculation qui s'appliquent à la fois aux systèmes dulcicoles, salins et artificiels; ces principes ont été dégagés des 19 chapitres précédents et des discussions qui ont eu lieu avec tous les participants de l'atelier au cours des pauses et des séances plénières. Le livre contribuera grandement à l'approfondissement de nos connaissances sur la floculation dans de multiples environnements .

Quels sont les résultats?

Les résultats exposés dans ce chapitre sont un synopsis de tout le livre et des analyses tirées de l'ensemble de l'atelier. Le chapitre apporte de l'information sur les principes généraux de la floculation, et les difficultés et les problèmes émergents de la recherche sur la floculation.

Comment ces résultats seront-ils utilisés?

Le chapitre figurera dans le livre « Flocculation in Natural and Engineered Environmental Systems » et apportera aux lecteurs des connaissances scientifiques et pratiques sur des questions relatives aux flocs dans divers milieux.

Quels étaient nos principaux partenaires dans cette étude?

L'étude a été réalisée en partenariat avec l'Université Ryerson et l'Institut océanographique de Bedford du ministère des Pêches et des Océans.

Opportunities, Needs and Strategic Direction for Research on Flocculation in Natural and Engineered Systems

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Abstract

In the history of environmental science, there has probably been no greater struggle than the attempt to control the impact of the sediment and solids generated by nature and human influence (including industrial processing) on the terrestrial and aquatic environments and on socioeconomics in general. Flocculation is a process inherent within both natural and engineered systems such as wastewater treatment and is simply the aggregating of smaller particles together to form larger composite particles via various physical, chemical and biological interactions. These larger composite particles behave differently in terms of their physical (e.g. transport, settling), chemical (e.g. contaminant uptake and transformation), and biological (e.g. community structure activities and metabolism) behaviour relative to their constituent individual particles due to differences in size, shape, porosity, density and compositional characteristics. Given these significant behavioural differences between flocs *per se* and their individual component parts, flocculation influences a wide array of environmental phenomena related to sediment-

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1 Introduction

The workshop, *Flocculation in Natural and Engineered Systems*, held in September of 2003 at the Canada Centre for Inland Waters provided a unique perspective of flocculation processes through the integration of current knowledge obtained from natural and engineered systems. This multidisciplinary workshop incorporated scientists from freshwater, saltwater and engineering systems/environments and allowed for a cross communication of ideas from disciplines that have largely remained isolated in their study of flocculation processes. This integration of ideas and methods provides researchers from different disciplines and work environments with different motivations in their effort to answer the very different questions dictated by the environment of investigation. The different approaches to the study of flocculation presented here allow individuals to look at it from an alternative perspective. With an integrated approach, new opportunities arise for flocculation research within all three environments.

As can be seen from the preceding chapters, flocculation plays an essential role in mediating the physical, chemical and biological properties of not only the sediment itself, but also of the aquatic or engineered system as a whole. As such, the flocculation process has significant environmental and socioeconomic implications. For example, flocculation plays an important role in sediment and associated contaminant fate and effect, reduces reservoir capacity and fisheries habitat due to increased sedimentation, is used as a remediation strategy for oil spills and toxic algal blooms, and dictates the efficiency of wastewater treatment systems. While untold billions of dollars are spent each year on issues for which flocculation is the key process, our understanding of the underlying mechanisms is still developing. The goal of this workshop was to improve our knowledge of flocculation and its role in what appear at first glance to be very different environments. The free exchange of methods, models and ideas between researchers has identified areas of convergence and divergence within the study of flocculation.

The workshop demonstrated that, in general, the important variables in the flocculation process are the same regardless of environmental constraints (freshwater, saltwater or engineered systems). Apparent differences lie in the perceived relative importance of these variables and in the specific approach used for their assessment.

It is clear that there are three basic principles and one emerging issue which are supported in all three environments. These are 1) that flocculation is agreed, at its most simplistic level, to be the aggregating together of smaller particles to form larger particles, 2) that successful aggregation occurs through mechanisms described by basic coagulation theory, and 3) that the substantive physical behavioural impact of flocculation is the modification (generally increasing) of the downward flux of sediments. The biology of flocculated sediment, particularly the microbial activity, is quickly emerging as an important issue; bacterial activities modify much of the physical, chemical and biological behaviour of the sediment particles and the system as a whole. The biological aspects of flocculation have, of course, always been an important issue in engineered systems (e.g. wastewater treatment) but are only in the last few decades being explored within the freshwater and saltwater environments as a significant mechanism influencing the flocculation process. Beyond these three principles and the emergence of biological activity as an important aspect of flocculation, all other aspects of this complex phenomenon were generally agreed to be ruled by site specific parameters culminating in unique structures and chemical and biological behaviours within the medium of transport. This chapter summarizes the outcomes of the workshop, and guides us towards a better understanding of the unifying principles of flocculation.

2 Unifying Principles of Flocculation

The workshop was structured so that three focus areas were addressed for each environment of study; (a) modeling, (b) physico-chemical and (c) biological aspects of flocculation. Based on specialty, delegates were divided into three breakout sessions to address one of these focus areas. Each focus group contained researchers from the freshwater, saltwater and engineering systems to ensure a cross communication of ideas between environments and to facilitate an understanding of the unifying principles of flocculation. Each focus group was provided the following five common questions to ensure continuity for the final plenary session;

1. What are the common/different theories or principles used in each environment of study to address the focus topic?
2. What methods of parameter analysis are common/different between each environment of study to address the focus topic? What are the important parameters to be addressed?
3. How have field and laboratory studies been employed to address the focus topic, and what are the similarities and differences between the environments of study?
4. Is there latitude to employ theories, methods, analysis, etc. not commonly used in one environment of study to another?
5. Are there emerging Issues?

The following sections summarize the discussions focused on these five questions during the plenary session.

2.1 *Common or different issues and principles*

Given the environmental differences and disciplinary differences of the researchers working in each system, it is not surprising to see that there are many different issues or principles considered by each. This section discusses those principles or issues for which there was agreement on their significance within flocculation research within all three environments.

2.1.1 *Definition of a floc*

While the simplistic definition of flocculation provided above is agreed upon, the expansion from this basic level to more complex structures is driven by system specific conditions including the dominant particle types or the constituent particle of focus. A wide range of constituent particles enter into flocculation and these are summarized in Chapter 2. Many of these were discussed within the workshop with differences evident between systems of focus. While not always the case, generally freshwater researches were concerned more with the inorganic fraction of the floc particles owing to the need to assess mass transport within rivers and lakes. The saltwater researchers, dealing with estuaries, continental shelf and open-ocean settings tended to focus on both the inorganic and organic fraction, while the engineering researchers were almost exclusively concerned with the biological fraction due to the focus of wastewater treatment. Examples of floc differences with regard to environments are aggregates delivered to rivers via overland flow or eroded from the bed (Chapters 3 and 4), marine snow (Chapter 11), estuarine turbidity maxima (Chapter 10), and engineered microbial flocs (Chapters 14, 17 and 19). All researchers from all environments of study, however, realize the importance of organic and inorganic colloids and microbial activity within their flocculation studies.

2.1.2 *Coagulation Theory/Floc Kinetics*

Coagulation theory is fundamental to the study of flocculation in all environments. The principle of small individual particles adhering and forming larger faster sinking particles underlies the study of sedimentation in all three disciplines. Within the workshop, it was obvious that the initial starting point of coagulation had been refined within each of the different environments to enable researchers to better understand the process they were studying. Much of the work being carried out in freshwater and saltwater ignores the initial onset of coagulation and concentrates more on the behaviour of established floc kernels. Most of the attention in those fields lies within the realm of physics (particle transport and collision) rather than chemistry (destabilisation of particles to make them sticky). In contrast, the initiation and control of coagulation is an essential part of engineered systems.

2.1.3 *Modeling with Smoluchowski Framework*

The majority of the modelling efforts for flocculation are centred on the Smoluchowski framework. The principles captured within the Smoluchowski framework appear to be universal, and the major emphasis within the workshop was on further development and application of these principles within respective disciplines. It was evident, however, that within engineering systems, modeling of the flocculation process is not extensively applied. This divergence from natural system modeling is owing to the process-oriented nature of engineered treatment systems (e.g. wastewater). Modeling which is performed in this environment tends to be based on the plant operation rather than on flocculation specifically.

The freshwater and saltwater disciplines share a common interest in modelling the formation of flocs in suspension (Chapters 8 and 12). Both disciplines require floc models to determine the subsequent transport and deposition of suspended material. Due in part to the somewhat recent realization that flocculation is an essential factor in freshwater, the majority of the modelling work has been carried out in marine environments. The roots for model development in the saltwater discipline are found in the classic case of flocculation at the saltwater interface of rivers. This simple, chemical based aggregation was well suited to application of the Smoluchowski framework, hence significant advances were made. The need to reconcile the rapid vertical transport of carbon in the open ocean and the presence of abundant flocs in freshwater has forced researchers in both areas to consider biologically mediated aggregation in their models (Chapter 13).

2.1.4 *Settling Dynamics*

Research from all environments places a strong emphasis on the understanding of floc settling dynamics. This is based on the knowledge that the ostensible effect of flocculation is the modification of the downward flux of sediments. Understanding, modeling and controlling settling dynamics has environmental, social and economic benefits. Examples stemming from the workshop include the removal of sediments and contaminants from engineered systems (Chapter 19), the development of estuarine turbidity maxima (Chapter 10) and infilling of reservoirs and destruction of habitat due to increased sedimentation (Chapter 4). Multiple other issues prevail throughout this book.

2.1.5 *Hindered Settling*

Hindered settling is a principle that applies mostly to the engineered system; however, it is also an issue within saltwater systems that have high sediment load. In the engineered system, microbial floc formation and gravity sedimentation of the synthesized biomass in secondary clarifiers of activated sludge plants are considered to determine the overall efficiency of this secondary wastewater treatment process. Hindered settling has plagued the activated sludge process since its inception and is related to solids separation problems, such as microbial bulking and foaming, settling difficulties of microbial flocs, and difficult dewatering of the sediment sludge. Hindered settling in engineered systems is most often reflective of a buoyant property due mostly to the trapping of water, bubbles and filamentous microorganisms (e.g. algae and bacteria) between/within floc particles.

Hindered settling within saltwater systems occurs when at high concentrations the return flow of water around settling particles creates an upward drag on neighbouring particles. At sufficiently high concentrations, hindered settling can keep sediment fluidized and prevent settling. In saltwater systems, hindered settling can lead to the development of extremely high concentrations, near bottom sediment layers, that can reduce boundary layer turbulence. This issue is discussed in detail in Chapter 10.

2.1.6 *Suspended Solids Concentration*

While agreed to be an important issue in all environments, it takes on different significance within each. Within the natural system, suspended solids concentration is important in the modeling of flocculation due to its impact on collision frequency, maintenance of maximal floc size, loading of receiving water bodies, and burial rates among others. Within engineering facilities such as those of wastewater treatment, suspended solids concentration is a critical parameter related to the maintenance of a specific sludge volume (important for effective operation), to an optimization of sludge dewatering properties and to an optimization of settling characteristics within clarifiers. See Chapter 19 for further discussion.

2.1.7 *Emphasis on Gross Morphology*

The reflection of gross morphology on an individual basis or through grain size distributions is employed more within flocculation research from the freshwater and saltwater systems. This is attributed to the needs for assessing particle transport and as such a need to understand how floc structure influences floc transport. In the engineered systems, the gross structure of flocs tends to be less important than the overall mass characteristics of sediment within, for example, activated sludge systems. The exception to this is, however, seen in research efforts centred on the development of a "designer" floc which will have specific physical, chemical and biological characteristics and which will optimize a given engineering requirement. For example, the formation of a population of more compact flocs with good settling characteristics and low water content will improve dewatering performance (Chapters 2, 3, 4 and 5).

2.1.8 *Microbial Activities*

The speciation of the microbial component, the microbial optimization of their own environment and EPS (extracellular polymeric substance) production are all related to microbial activities within the floc. Within the majority of wastewater engineering applications, the activity of the microbial component is paramount to the development and behaviour of flocs within the system (Chapters 14 and 15). The principle of the great importance of microbial activity within natural flocs has only more recently been explored (Chapters 2 and 6) with the saltwater research being more advanced in this regard than the freshwater systems due largely to the microbial research involved in marine snow investigations. Microbial activity is fast becoming the dominant phenomenon of interest within flocculation research in both natural systems because of its strong influence on the physical, chemical and biological activity of the sediments and system as a whole (Chapters 2 and 6).

2.1.9 *Floc Stability*

Stability is a critical principle within flocculation research in all environments owing to its obvious influence on particle transport, erosion and engineered system performance. While floc formation is fairly well constrained, floc break-up under applied stress is not well understood. As such, it was agreed that one of the greatest needs in flocculation research is the need to develop methods to measure properly this floc characteristic (see section 2.2.5). Such characterization would aid greatly in the effective modeling of flocculation processes within all three environments (Chapter 16)

2.1.10 *Response to Stressors – Function/Structure*

In essence this is the heart of all flocculation research regardless of environment. Traditionally within the natural environments, research is centered on a sediment's response to an applied or changing shear stress with concomitant influence on floc development and transport (Chapter 5). This is particularly true for the modeling aspect of flocculation research (Chapter 8). From the engineered system, however, the stressors are often related more to nutrient or contaminant fluxes which can modify the performance of a system by influencing floc structure and biological activity (Chapter 17) (physical shear is obviously also an issue). The use of a stressor such as ultraviolet radiation has been used successfully in disinfection (Chapter 18). More recently, researchers studying natural systems are beginning to assess the interaction of contaminants with flocs. This is an emerging issue within floc models which require additional parameters to predict spatial and temporal contaminant changes within sediment systems.

2.1.11 *Chemical Gradients*

The realization that chemical gradients may be set up within a floc via diffusional or advective processes is primarily restricted to engineered systems where contamination interaction is a large and expanding area of research. Analysis of gradients within natural systems stems largely from biofilm research (Chapter 6) where such issues are important at sediment water interfaces. It is now understood that many of the processes occurring in biofilms also occur in flocs. In essence flocs can often be considered suspended biofilms (Chapters 2, 6 and 14).

2.2 ***Common or Different Parameters and the Methods Used to Investigate Them***

There are numerous parameters that are measured in the study of flocculation. The majority of these are common between all three environments of study. As expected, because of the very different physical, chemical and biological constraints within these environments, there is disagreement on the relative importance of these parameters. There is a movement away from relying on bulk measurements to assess sediment characteristics, to that of assessing individual flocs within a population to gain a much more in-depth understanding of how floc structure will influence floc behaviour or system performance as a whole.

Below, are the most important floc parameters influencing flocculation, as agreed upon by the delegates, and the relative importance of each parameter to each environment. There are some standard methods for the assessment of these parameters; however, different approaches are often taken by researchers who are driven by constraints imposed by external variables and by the accessibility of state-of-the-art technologies. Often location, concentration and size differences (e.g. colloid vs. particulate) lead to a requirement for different m ethods. Rather than provide in depth discussion on the various methods for the measurement of these variables, the reader is referred to Chapter 1 for an overview and insight into the methods applied to the study of flocculation.

2.2.1 *Floc Size*

Floc size is the most common parameter which is used within all environments and is often manifested as a distribution (by volume or number) or as a statistical representation of a distribution such as median size or maximal floc size. One must be careful in characterizing flocs by volume distributions only, due to the overriding influence that a few large particles can have on the distribution. Often an insignificant number of particles (relative to the total number) can represent significant volumes of the total sample. Floc size is a key component of any model for the prediction of sediment transport, deposition and erosion. Floc size will also have an impact on filter feeding organisms, trapping efficiency of gravel beds and will have a bearing on sludge volume within wastewater treatment systems. Chapters 3, 4, 5, 9, 17 and 18 all utilize floc size as in important part of the research investigations.

2.2.2 *Settling Velocity*

While floc size is the most common physical characteristic measured, settling velocity is the most common behavioural characteristic measured. It is also the most critical parameter for transport models and is generally measured using *in situ* or laboratory settling columns. It is acknowledged that older methods such as Owens tubes, which determine settling velocity from clearance rate, must be used with caution since they are based on the derivation of Stokes' equation that assumes solid spherical units. Flocs, as amply demonstrated in this book, are not solid spherical units. Differences between settling velocities derived from settling columns can vary from in situ velocities by an order of magnitude. The critical role of settling velocity in modeling sediment transport and for the assessment of an engineered system's efficiency can be seen in Chapters 4, 5, 8, 10 and 11.

2.2.3 *Density and Porosity*

Density and porosity are two variables which are highly related and which will have an effect on the transport characteristics of the sediment (Chapters 3, 4, and 5). As porosity increases, density decreases primarily due to an increase in pore water. Engineers are very aware of this parameter as it will dictate the dewatering efficiencies for sludge removal. Particle density is also a critical variable for most modeling efforts regardless of environment. There is no standard direct measurement of these two parameters. Generally they are estimated, based on measuring the settling velocity of known size particles and then using Stokes' equation (or a derivation thereof with a correction factor), from which the density is derived. Porosity has been derived by a mass balance between the dry floc density, wet floc density and the water density (Chapter 1). Direct measurements of porosity are irrelevant due to the tortuous nature of pores as dictated by the EPS matrix within flocs (Chapter 2).

2.2.4 *Shape (Fractals)*

The shape of a floc is often used to help explain the settling/transport behaviour of flocs. Most often this is done by using a shape factor such as roundness or sphericity as a correction factor for data from settling equations such as Stokes' Law. Fractal dimensions are also used and these are believed to be a more sensitive a ssessment of particle shape and roughness. There are many variants on assessing the floc dimension, with the majority based on the slope of the line between surface area and perimeter for a population, or individually as the change in perimeter with incremental increases in measurement steps around the floc. There are many more variations for which the reader is referred to Chapters 4 and 5.

2.2.5 *Strength*

This parameter relates back to the stability issue from Section 2.1.9. There is no defined standard method for the measurement of floc strength nor is there a standard unit of measurement. Atomic force microscopy (AFM) is one technique which demonstrates promise in this regard (Chapter 16); however, other means for the characterization of stability are needed. The majority of stability work performed to date has been based on the correlation between measures of shear and floc size (Chapter 5). This relationship has been restricted to laboratory studies where often unrealistic shears are applied. A field method of assessing floc stability is critical. It must, however, not be based on the assessment of changes in volume distributions as these are severely biased towards larger flocs and will provide erroneous relationships (Chapter 1).

2.2.6 *Stickiness*

This parameter is similar to strength in that there is not a standard unit of measurement or method of measurement. Once again AFM is fast becoming the method for its assessment (Chapter 16); however, it is not ideal as it can be very expensive to use. On occasion carbohydrates, uronic acids or other EPS components are used as a surrogate variable to suggest a degree of stickiness within a population of flocs. Assessment of individual floc stickiness is still, however, an elusive, but highly sought after, variable. Stickiness and a tendency to flocculate are related. In this regard, some progress has been made to show relationships between flocculation, system free energy and the physicochemical properties of floc. The level of effluent suspended solids in biologically treated wastewaters is a strong indicator of flocculation and is related to the physicochemical properties of microbial floc formed in the aeration tank of wastewater treatment systems. Increasing experimental evidence indicates hydrophobic interactions play an important role in flocculation (Chapter 19).

2.2.7 *Microbial Ecology*

Microbial ecology is currently receiving a great impetus from environmental genomics and the use of specific probes in conjunction with analytical microscopy (Chapters 1, 6, 15). Environmental genomics is a genetics-based, interdisciplinary field of research that seeks to understand external factors affecting organisms when they are exposed to environmental stresses, such as contaminants and pathogens. Host responses to these stresses include changes in gene expression and genetic products, changes that culminate with alterations in host phenotype, including host EPS composition.

Until recently it has been very difficult to determine the true level of diversity of microorganisms in both natural and engineered ecosystems. However, advances in molecular biology have now made it possible for microbiologists to use novel tools in studies of the ecology, diversity and evolution of microbes. The advantage of using molecular techniques is that bacterial cells present in a complex microbial community can be detected and classified without any necessity for their cultivation. Thus, comparative sequence analysis either provides researchers with the phylogenetic framework for unequivocally placing unknown bacteria, or allows the development of tools such as fluorescent hybridization (FISH) DNA probes to identify the large number of uncultured bacteria seen under the microscope in natural environments. However, the limited number of probes that can be applied in one hybridization experiment becomes a distinct bottleneck when this technique is used for community analysis where a high level of phylogenetic resolution is required. The fact that many of the molecular methods described are not widely accessible to all, as well as the difficulties in mastering these methods, present challenges to floc researchers wishing to fully employ these in their studies.

2.2.8 *Surface Properties*

The composition of flocs includes silts and clays. microorganisms, EPS and organic and/or inorganic colloidal particles. EPS, salt bridges, a backbone of filamentous bacteria, or a combination of all three, account for the integrity and mechanical stability of microbial floc. A multitude of factors (e.g. nutrient regime, oxygen, and pH) can affect both the population dynamics and floc structure. Increasingly, more emphasis is being placed on the structure, composition and the physicochemical properties (e.g. surface properties) of flocs and the suspending medium as these may strongly influence the behaviour (e.g. bioflocculation, settling properties, biosolids management or contaminant removal) of biomass.

The role of surface properties in floc interactions is particularly important in understanding microbial floc formation (Chapter 19). The proposed mechanisms for microbial floc formation can be classified into five types: 1) charge neutralization; 2) hydrophobic interaction; 3) polymer bridging; 4) salt bridging; and 5) the surface thermodynamic approach. The polymer bridging mechanism has received the greatest attention (Chapters 7 and 9); it involves the entanglement and adsorption of microorganisms by the EPS. The differences between these models lie in which of the surface properties is considered to be most important, and how a particular parameter is affected by nutritional and environmental conditions.

A wide variety of methods have been applied to examine the gross morphological properties of flocs, their ultrastructure and physicochemical properties (including hydrophobicity and surface charge), and the composition of their EPS (Chapter 1). Greater emphasis in the future should be directed to applying these methods across all floc types, as well as to increasing the standardization of methods and techniques, for permitting comparative analysis of different properties amongst different floc types. The desired outcome will be to have reliable tools and a comprehensive knowledge of floc that can enhance cost and energy efficiencies, optimize processes and sustainability, and better manage risks related to important flocculation-mediated environmental processes in environmental and engineered systems.

2.2.9 *Large Number of Common Variables*

There are a host of common standard variables for the three environments of study. These typically are pH, temperature, DOC, POC, BOD, COD and ionic strength and do not need elaboration here.

2.3 ***Field and Laboratory Studies***

A discussion on the similarities and differences of field and laboratory studies between environments demonstrated a strong split in needs. Generally within the engineering systems, research into flocculation is exclusively lab based, given the nature of the requirements. Within the natural systems (freshwater, saltwater), there tends to be an emphasis on field work; however, there is still some important experimental laboratory work oriented ostensibly around modeling issues. Laboratory experiments often take the form of flume work (Chapter 5) or shear related experiments (Chapter 8). Of course any modeling efforts generated from laboratory experiments will need to be validated within the field. The greatest difficulty in using laboratory studies to represent the "real world" is in scaling the findings from the laboratory to the field. This difficulty in transferability is likely to be related to scaling differences in turbulence intensity between the two environments (laboratory vs. field) and the impossibility of accounting for the myriad of uncontrolled variables within the field. Nonetheless natural and engineered laboratory experiments do allow for the assessment of the dominant mechanisms influencing flocculation.

The single most difficult issue, regardless of a field or laboratory approach, is the sampling of flocs for investigation. The issue lies around maintaining the integrity of the flocs during sampling, transport and analysis. It was interesting to note differences in the focus of the groups studying natural systems and those studying engineered systems. While natural systems studies concentrated more on in situ studies, engineered systems were far advanced in the study of individual flocs. The difference in emphasis may reflect the difference in the stability of the flocs in natural and engineered systems. While flocs from batch reactors and other controlled and re-circulating systems are relatively robust, flocs in both marine and freshwater systems are ephemeral, making transport to the lab extremely problematic. Generally, flocs are presumed to be inherently unstable and prone to break up. Floc stability changes, and changes to resulting morphological correlates of stability, can occur quickly during storage of a sample prior to analysis; no bulk storage prior to analysis is recommended. Methods are now available which transplant laboratory stabilization techniques (common to microscopy) to the field, thus allowing minimal perturbations and prolonged sample storage prior to analysis. Stabilization is, however, only feasible for small sample populations. Sampling of flocs in the natural system is made more difficult due to uncontrollable external variables such as weather and spatial and temporal variations.

Through the preceding chapters, this book provides an extensive cross section of both field and laboratory based work. It is evident that both approaches are required and need to be integrated in order to more fully understand the complex issues of flocculation in natural and engineered systems.

2.4 *Latitude for Linkage of Freshwater, Saltwater and Engineering Principles, Methods and Analysis.*

From the workshop and from the preceding papers, it is evident that there is significant latitude for overlap in the use of principles, methods and analysis between the freshwater, saltwater and engineered systems. The greatest potential for the transfer of technology is with regard to microbiology. As stated earlier, it was agreed that the microbial consortia play a large role in controlling floc structure and behaviour. The engineered system has been the leader in the assessment of floc microbiology and, as such, lends great potential to assist the freshwater and saltwater environments in developing methods and indices that would provide further insight into flocculation processes for these environments.

Specifically, areas that could be developed are genomics, molecular and microscopic methods within freshwater and saltwater systems.

Further, it was also agreed that there was scope for integrating the rapidly evolving approaches of nanotechnology, and surface and materials science into all systems. Scanning transmission X-ray microscopy, using synchrotron radiation, has shown great potential to map floc architecture and chemistry at high resolution in three dimensions. Atomic force microscopy is a promising new tool for measuring the interaction forces between one colloidal particle and another. Advanced optical microscopies, including confocal laser scanning microscopy, are permitting the integration of topographical, chemical and three-dimensional structural information, with molecular and ecological determinants that determine floc characteristics

Often models have remained somewhat mutually exclusive to the environment or issue that they were used to investigate. Many if not all of these models have at least some common components or assumptions. Given this realization, it was discussed that a base-line sediment transport model with a common modeling framework would be of great advantage for the investigation of floc related issues. Such a base model would greatly improve cross linkages between environments and allow for transfer of technology between environments for expanded and improved assessment capabilities. Such an approach would also make it easier to integrate models for a more holistic look at the greater environment. For example, it was agreed that great utility would be achieved if models of rivers, estuaries, continental shelves and open oceans could be linked given their real world connection.

Finally, it was agreed that the natural systems have traditionally dominated the floc research approach which uses *in situ* technology to investigate floc form and behaviour. *In situ* methods for measuring particle sizing and settling velocity are becoming common place (see Chapter 1) and often use direct observation (video) or indirect (laser particle sizing) methods to make assessments in a temporal or spatial context. It was agreed that the potential exists to implement similar systems in-line or in-tank for many engineered systems such as wastewater and drinking water treatment.

2.5 *Emerging Issues and Challenges*

While microbiology is an area of commonality, it is still an emerging issue, particularly within the freshwater and saltwater environments. Issues which will require further development reside in the efforts to deal with heterogeneity and diversity of the floc microbial population and their impact on floc behaviour. In particular, we must ascertain which bacterial species play the most important roles in creating floc architecture, and which environmental signals modulate their efforts. Within the engineering field there is the need to optimize particle specific conditions toward the development of the "designer floc". The designer floc will be the product of a bioengineered system for promoting the formation of flocs which are functionally adept at achieving a desired result such as specific contaminant removal or effective settling.

Contaminant interactions with sediments and flocculated particles in particular, are poorly understood. This has been effectively born out of the traditional bulk sample approach to contaminant concentration assessments. The effective micro-scale biogeochemical pathways and mechanisms which mediate the uptake, transformation and fate of contaminants in aquatic and engineered system flocs remain largely unknown. In order to develop and initiate effective contaminated sediment remediation strategies, it is essential that the micro-scale processes of contaminant interaction be ascertained. Further, little is known about the interactions of pathogens and hosts within flocs and how the floc influences pathogen viability, proliferation and activation within sediment water systems.

Further emerging issues relate to source area identification of sediments and the role that flocs formed in the water column versus aggregates formed in the terrestrial environment (water stable soil aggregates) play in the transport of sediment and associated contaminants. Further, there is a lack of knowledge on how a floc's biogeochemical characteristics influence bed sediment development and biogeochemical characteristics, particularly in terms of biofilm development, contaminant assimilation and transformations, and bed stability.

The advancement of floc research in all environments will continue to benefit from the development of in-situ techniques, as these methods allow for the unobtrusive real time assessment of changes in floc population characteristics. In so doing, water managers can adjust protocols to provide for a more effective management of water resources. Such management could pertain to sediment remediation efforts or to wastewater treatment system operations.

Contaminated sediment and aquatic remediation is increasingly employing flocculation principles and formation within technologies. For example, promoting flocculation of oil with clay has been successfully used for oil spill remediation, thus adding it to a list of available strategies for environmental clean up. Other technologies are emerging which also embody flocculation as an integral part of the technology, such as the addition of clay to toxic algal blooms to promote flocculation and thereby reduce their impact on commercial fisheries. There is great potential for flocculation research to aid in the development of other remediation technologies in the future.

Finally floc strength is realized to be a critical characteristic in relation to sediment and contaminant transport; however, there is no suitable method of measuring it. This in conjunction with the microbial activity of flocs was viewed as the most urgent challenge facing flocculation researchers.

3 Conclusion

Sediments within both natural (freshwater and saltwater) environments and engineered facilities play significant environmental, economic and public health roles in society. The majority of priority pollutants including heavy metals and organic contaminants (such as PAHs) are associated with sediment particles. The beneficial use impairment of many aquatic environments, including every Area of Concern as defined within Remedial Action Plans of the Great Lakes basin of North America and elsewhere internationally, are related to contaminated sediments. These beneficial use impairments include swimming, boating, fishing, aesthetics, odour and benthic community impacts. Substantial sums of money are invested each year in the remediation of contaminated sites in an attempt to increase beneficial uses. Within engineered systems such as drinking water and wastewater treatment facilities, the removal of solids is the key aspect of treatment and, as such, here too significant sums of money are invested to provide the most efficient operating system possible.

Within both natural and engineered systems, when sediment issues are in question it is inevitable that flocculation will be a dominant process that will contribute to, or control the issue. This is because the majority of cohesive sediments within natural systems are transported and eroded within a flocculated state and the floc is the model form of solids for most engineered systems. Given that the structure of a floc will influence its physical (transport), chemical (uptake/transformation of contaminants) and biological (community dynamics and biochemical activities) behaviour, it is not surprising that flocculation plays a dominant role in influencing the environmental, economic and public health impacts of sediments. While this is widely accepted, there is still a fundamental lack of knowledge related to many aspects of the flocculation process and the resultant floc and as such our abilities to manage water resources are impaired.

Through the sharing of information between researchers of different disciplines and environments, the workshop has contributed to improving our knowledge of the greater flocculation process and impact within the freshwater, saltwater and engineered systems. The workshop has demonstrated the strengths and weaknesses within floc research in the three environments and has pointed to the need for continued collaboration between researchers. Of particular note is that cross-environment multidisciplinary studies would be of great benefit in ascertaining the universality of flocculation processes and impacts. Presently such cross-environment studies are very limited in scope. Continued development of new and innovative methods which can be effectively used between environments will be essential to the advancement of flocculation research.

The contributors to the Workshop on Flocculation in Natural and Engineered Systems have provided herein some integral elements to advancing our understanding of flocculation processes; however, the work has only just begun. By integrating resources, expertise and ideas, researchers will continue to advance our knowledge in this vitally important environmental, economic and public health issue.

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