Ministry for Primary Industries
Manatū Ahu Matua

LITERATURE REVIEW OF ECOLOGICAL EFFECTS OF AQUACULTURE

Hydrodynamic Effects

Photo courtesy of Phil Kirk

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Hydrodynamic Effects

11

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11.1 Feed added (salmon, kingfish, hapuku)

11.1.1 Overview of hydrodynamic effects

Sea-based aquaculture of finfish uses cages in coastal or offshore waters. Hydrodynamics conditions are an important determinant of the suitability of a site for finfish production, as well as the spatial size and magnitude of the environmental effects. Here, hydrodynamics refers to the physical attributes of the water including:

- currents;
- stratification;
- waves.

Stratification refers to the layering of water caused by differences in temperature and salinity.

The most recognised and studied impact of finfish aquaculture is the changes to the benthic environment due to deposition of waste feed and faeces. Other issues include oxygen depletion and ammonium increases in the water column.

Current speed is a key factor in determining the exchange of water through the cage, areas over which deposition occurs and also in the re-suspension of material. Currents also determine where dissolved material is transported and how it is dispersed, with the drag from cages affecting currents, causing wakes, turbulence and flow diversion. Low velocity areas have a higher risk of issues of deposition, oxygen depletion and ammonium buildup.

Stratification can play a strong role in oxygen depletion by restricting the vertical transport of oxygen from the surface to deeper waters. There are likely to be interactions between stratification and fish cages in the form of selective blocking, restricted underflow, generation of internal waves and vertical mixing. Fish swimming may also play a role in enhancing mixing and causing upwelling within cages.

Wave energy is attenuated by fish cages, and this will result in a shadow of reduced wave activity behind the farmed areas.

While some physical effects may affect other physical processes directly, for example, attenuation of wave energy affecting surf or coastal sediment transport, it is generally more important to consider how physical effects influence ecological processes. For example, the physical effect of reduced current speeds caused by drag from fish cages may result in an increase in the flushing time of a bay. This in turn may lead to increased nutrient concentrations. Reductions in wave energy near the coast may have significant effects on coastal habitat.

The physical hydrodynamic effects will interact strongly with pelagic and benthic processes. Selection of suitable indicators for physical changes should ideally be based on their relative importance in determining the habitat for ecological communities in an area. However, it is this link between the physical and ecological changes that is often the least understood.

11.1.2 Descriptions of main effects and their significance

11.1.2.1 Reduction in currents and redirection of flow

Table 11.1: Reduction in currents and redirection of flow due to feed-added aquaculture operations.

Description of effect(s)	Water speeds are reduced upstream, downstream and within finfish cages. There is likely to be a reduction in tidal, wind-driven and residual current speeds over embayment scales. However, there may be local increases due to accelerations of flow around or beneath cages. Deposition will be spread over larger areas but less intensely in high velocity areas. Bed shear stresses may be increased or decreased depending on cage layout, porosity and water depth. Bay flushing times may be increased or decreased depending on the size and location of finfish cages. Low velocity areas are more likely to experience high deposition rates and oxygen depletion, along with higher concentrations of dissolved or suspended waste products.
Spatial scale	*Local bay-wide* and *regional.*
Duration	*Short term.*
Management options	• Effects of finfish structures on local and embayment-scale currents can be predicted using existing data or analytical and numerical models. This information can help inform ecologists and stakeholders of possible physical changes from the introduction of new structures and ways to mitigate effects. • Monitoring of currents before and during staged development could be used to ensure that effects match predictions, but care will be needed to ensure that reference sites are located beyond areas affected by the development. The duration of monitoring should be sufficient to capture a range of tide, wind and stratification conditions. These conditions should be comparable between the monitoring periods before and during development.
Knowledge gaps	• Further research is required to relate drag on cage elements to changes in flow beyond the cage. • The effect of fish stock and fish behaviour on currents is not clear. • More research is required on stratification, which will influence how water flows around cages. Horizontal density variations may also drive currents. • Knowledge of the connection between ecological responses to changes in currents needs to increase.

* Italicised text in this table is defined in chapter 1 – Introduction.

Summary

Water currents are a key factor for transport of nutrients, plankton, larvae and for dispersal of material. Currents near the bed will determine whether material is deposited, eroded or re-suspended. Organisms may also have habitat preferences influenced by water speed. Water currents are therefore a key driver of ecological processes. Both pelagic and benthic effects from aquaculture are mediated by a site's hydrodynamics, for example, water depth, current speed and direction (see Chapters 2 and 3). This affects, for example, both the location of material deposited on the bed and its possible re-suspension by bottom currents. Strong bottom currents may result from large (spring) tides or less-predictable events such as strong winds, storm surge, and internal waves.

The most common types of sea cages used for finfish aquaculture are rectangular cages and circular pens, where cylindrical nets are hung from a floating ring. Rectangular cages may be rafted together, while circular cages may be connected or separated. Internationally, large cages are more typically circular. At present, in New Zealand, rectangular cages are more common.

Fish cages cause a partial blockage to flow leading to deceleration of the approaching flow and formation of turbulent downstream wakes (Helsley & Kim 2005; Venayagamoorthy et al. 2011). The spread of plumes of dissolved waste products from fish cages is enhanced by the flow modification caused by the cage drag (Venayagamoorthy et al. 2011). Dispersal is further complicated by shoreline topography, bathymetry, tidal oscillatory flow, wind and Coriolis forcing (Venayagamoorthy et al. 2011).

Flow will also be diverted horizontally around and/or vertically beneath cages (Merceron et al. 2002; Johansson et al. 2007). Similar flow diversion occurs for other forms of aquaculture, including long-lines (Gibbs et al. 1991; Boyd & Heasman 1998; Plew et al. 2006). Increases in velocities beneath a farm may increase the shear stress on the bed, increasing the likelihood of re-suspension of sediments and deposited material and affecting the depositional footprint (Black et al. 2008). Laboratory experiments on porous obstacles show that the acceleration beneath the obstacle and, consequently, increases in bed shear stress, depend on the porosity and depth of the obstacle (Plew 2011a). Density stratification has also been observed to influence flow through fish cages (Johansson et al. 2007) and other porous structures (Plew et al. 2006).

Drag from cages will influence tidal, wind and residual currents beyond the cage perimeters. This may lead to changes in bay flushing times and transport pathways. The horizontal diversion of flow around cages or groups of cages can result in local increases in water speed, as seen for mussel farms (Plew 2011b). Cages placed where currents are strong have greater drag than those in slower velocity environments. Cages placed in constricted areas, such as narrow portions of a bay, have a greater influence on flow than in wider areas as there is less room for flow to divert around the cages. It may be possible to position or arrange cages in such a way as to promote flushing of parts of a bay (Plew 2011b). Model studies of mussel farms show that the effects of drag from suspended obstacles can have effects on current speeds that extend over the whole bay and even beyond the bay (Plew 2011b). The effects of cages on hydrodynamics will be cumulative, but the effect of individual cages will not necessarily be equal.

In addition to the physical and ecological consequences of the effect of finfish cages on currents, current speeds also have an influence on the cages. Forces on nets and moorings are increased by strong currents, placing greater emphasis on engineering design to prevent damage to the structure, displacement of fish stock or loss of fish.

The presence of fish inside the cage can also alter flow, in addition to the flow disruption caused by the nets (Chacon-Torres et al. 1988). Swirl caused by fish schooling is likely to generate an outward flow through the side of the nets. There is no known study that investigates whether drag is increased by fish presence or behaviour.

Local changes in currents are almost certain. Embayment-scale changes in circulation are highly likely in small bays or bays with several cages. The physical effects on currents will persist for the duration that the cages are in place. Return to ambient conditions on removal of all cages will be nearly immediate. Ecological consequences of modified currents may persist for longer. For example, if the composition of ecological communities, or the abundance of species, has altered as a result of changes to currents, recovery from these changes could be slow. It is possible that some changes could be permanent.

11.1.2.2 Stratification

Table 11.2: Effects on stratification due to feed-added aquaculture operations.

Description of effect(s)	Stratification is the layering of water bodies due to differences in density as a consequence of temperature and salinity. Stratification varies seasonally and is also influenced by meteorological and climatic conditions. Strongly stratified waters tend to resist vertical mixing and overturning, making them more susceptible to ecological issues such as oxygen depletion or trapping of nutrients and dissolved material, including ammonium within layers. Finfish cages alter stratified water bodies through: • blocking or diversion of some water layers; • generation of internal waves; • possible enhancement of vertical mixing.
Spatial scale	*Local* and *bay-wide.*
Duration	*Short term.*
Management options	• Site selection criteria to be set in conjunction with ecological issues that are mediated by hydrodynamics, for example, benthic deposition. • Monitoring of temperature, salinity and oxygen profiles.
Knowledge gaps	• It is not known whether changes in water clarity caused by removal or addition of suspended or dissolved material have a significant influence on temperature through absorption of solar energy. • The magnitude and spatial scales of changes to stratification need to be better understood in order to determine any ecological consequences. • The interactions between stratified flows and finfish cages are poorly understood. More research is required to understand: – how stratification affects the diversion of flow beneath or around a cage; – the interactions caused by multiple cages; – whether cages induce significant vertical mixing; – if cages can be designed to change vertical mixing; – if fish motion changes vertical mixing.

* Italicised text in this table is defined in Chapter 1 – Introduction.

Summary

The density of water is primarily determined by salinity and temperature. Less dense water (warmer or fresher) tends to rise and lie over more dense (saltier or colder) water, this is called stratification. Stratification is important ecologically as temperature and salinity can be a factor in pelagic and benthic habitat suitability for organisms or communities (Abookire et al. 2000; McLeod & Wing 2008). Oceanic and coastal waters are nearly always stratified to some degree due to the effects of river inflow, mixing of different water bodies and heating and cooling. The degree of stratification may vary on daily to seasonal time scales. Longer term climate conditions (e.g. El Niño/La Niña-Southern Oscillation) will also influence stratification.

Stratification has been observed to alter current and oxygen profiles within cages (Johansson et al. 2007). Both cultured fish and wild fish also alter depth in response to temperature, salinity and currents, all of which can be affected by stratification (Abookire et al. 2000; Johansson et al. 2006). A potential issue with caged finfish is oxygen depletion (Beveridge 2004). Stratification resists vertical mixing, and oxygen depletion below the pycocline (the depth of greatest change in water density with depth) may be persistent (Johansson et al. 2006; Johansson et al. 2007), potentially affecting large areas. Stratification will also influence the dispersal and dilution of dissolved waste products, including ammonia. In a strongly stratified environment, dissolved material will remain above or below the pycnocline depending on its source depth.

There is likely to be an effect of cages on stratification due to flow resistance, and possibly enhanced vertical mixing due to shear and turbulence (Plew et al. 2006). Fish-induced swirl may also increase vertical mixing and cause upwelling within cages (Chacon-Torres et al. 1988). Field observations have shown that porous obstacles interact with stratification, resulting in changes in the depth of isopycnals[1] (Plew et al. 2005; Plew et al. 2006). Preliminary laboratory experiments indicate that strong stratification will resist vertical diversion around porous obstacles and vertical mixing. Consequently, stratification needs to be considered alongside flow diversion. Laboratory experiments also indicate that internal waves can be produced when stratified water moves past a porous obstruction. These internal waves can travel long distances. It is not yet clear whether cages generate significant vertical mixing, although the degree of mixing will also depend on the strength of the stratification relative to water velocities.

Water temperature is primarily driven by heat exchange with the atmosphere, absorption of solar radiation and radiated losses from the surface. Other causes of temperature variations are river inflows, or transport and mixing of waters from oceanic sources. There is a theoretical potential for finfish to increase water temperature through dissipation of turbulence generated by swimming, but this is expected to be insignificant and likely to be below detection limits. Finfish are unlikely to have a direct effect on salinity as they neither consume nor produce salt.

There is potential for changes in solar heating due to changes in water clarity. The depth of light penetration into the water column depends on various optical properties of the water including the concentration, size and nature of suspended and dissolved material. Water turbidity may be increased due to fish farming, particularly if there is waste feed material (Mantzavrakos et al. 2007).

The influence of stratification depends on how great the differences in water density are and the strength of other physical process that drive water motion, such as tides and weather. The spatial scale of the effect of cages on stratification is unknown. Blocking and diversion will be most apparent within and near the cages. Internal waves may travel a considerable distance (km's). Mixing is most likely to occur within and immediately downstream of the structures. However, this mixed water will be transported by currents, and the effect may become more pronounced over several tidal cycles if water is repeatedly advected through cages.

Generally, temperate coastal environments experience a wide range of salinity and temperatures, and it is difficult to predict whether changes in stratification will have significant ecological effects without first understanding the magnitude and spatial scales of these changes. The physical effects on stratification will persist for the duration that the structures and crop are in place. Return to ambient conditions on removal of all structures will depend on the length of time that water is replaced within the embayment but is expected to be less than one year. Ecological consequences of changes to stratification may persist for longer; for example, if the composition or abundance of species within ecological communities has altered as a result of the effects of cages on stratification, it is not clear how long recovery to the original community condition may take.

Future research could first assess how strongly stratification is influenced by fish cages (and the fish stock), and how far these effects can be detected. Then predictive models or tools can be developed. Consideration can be given to cage design or farm layouts that enhance or minimise vertical mixing depending on what ecological criteria are of concern.

[1] Isopycnals are surfaces of constant potential density. Water that lies on the same isopycnal has the same potential density. Isopycnals may be thought of as similar to contours of elevation on a topographical map, albeit in three dimensions rather than two. In the absence of wind, currents or motion, isopycnals would normally be horizontal. The term "potential density" refers to the density of water at a reference pressure, such as at atmospheric pressure. Potential density is a property of the composition (primarily temperature and salinity) of the water. Pressure (from the weight of overlying water) has a small effect on the actual in situ density due to the slight compressibility of water. This change in density due to pressure is dynamically unimportant.

11.1.2.3 Wave dampening

Table 11.3: Wave dampening due to feed-added aquaculture operations.

Description of effect(s)	• Wave energy transmission is reduced as wave energy is reflected and attenuated by fish cages. • A wave shadow of reduced wave energy will extend down-wave of the cages. • Reduced wave energy may affect shoreline habitat and sediment transport.
Spatial scale	*Bay-wide* to *regional.*
Duration	*Short term.*
Management options	• Thresholds for acceptable wave attenuation could be set to protect ecological communities. • Predictions of wave attenuation using analytical or numerical models. • Monitoring of wave attenuation before and during staged development. • Wave attenuation or reflection could be reduced by manipulating cage design, flexibility or net porosity.
Knowledge gaps	More measurements of wave attenuation by finfish are required to develop and validate predictive models. There is also a lack of knowledge of: • the wave attenuation by entire cages (present research focuses on individual net panels or the structural response of cages); • how the arrangement of multiple cages affects wave attenuation; • if wave attenuation differs between stocked and unstocked cages; • whether data on the structural response of cages can be used to estimate wave attenuation or reflection.

* Italicised text in this table is defined in Chapter 1 – Introduction.

Summary

The environmental significance of cage-induced wave attenuation includes possible changes to sediment transport, beach erosion and replenishment, and changes in habitat for species that have acclimatised to wave conditions.

While much of the literature on the subject of fish cages and waves focuses on the effect of the waves on the structure, fish cages do reflect and dampen wave energy (Chan & Lee 2001; Lader et al. 2007). The data published to date focus on individual net panels rather than cages or arrays of cages. The reflection and attenuation of wave energy is affected by net porosity and flexibility (Lader et al. 2007). Studies of floating cage breakwaters show that reflection normally accounts for the majority of the reduction in wave transmission (Massel 1976; Yu 1995). However, more flexible buoyant structures offer far greater dissipation with very little reflection (Seymour & Hanes 1979; Williams & McDougal 1996). An analogy can also be made to other floating structures, such as kelp (Dalrymple et al. 1984; Asano et al. 1988; Kobayashi et al. 1993), or suspended aquaculture where wave energy attenuation has been found to be frequency dependent, with greatest attenuation of short period waves, while long period waves that penetrate deeper into the water column lose less energy (Plew et al. 2005).

Wave attenuation will manifest as a shadow of reduced wave heights extending down-wave from cages. The cage-wave shadow will be of limited size as wave energy will refract horizontally from regions not influenced from the farm. The observed reduction in wave height will decrease with distance from cages. There is currently no guidance on the size of any wave shadow, or how this will relate to cage dimensions, stocking density, cage design and water depth.

Future research could be conducted on the effects of full-size fish cages and arrays of cages on the attenuation and reflection of wave energy to improve knowledge of wave effects. Potentially important fundamental research could focus on, for example: how attenuation/reflection depends on wave size and period, whether cage properties or design can be used to maximise or minimise wave attenuation, if fouling significantly changes wave effects and if the fish stock has any significant effect on waves.

Some degree of wave attenuation will occur for any fish-cage structures with surface or near surface components. The effect may be undetectable for individual cages, small farms or in sheltered areas. The physical effects on waves will persist for the duration that the structures and crop are in place. Return to ambient conditions on removal of all structures will be nearly immediate. Ecological consequences of modified wave climate may persist for longer. For example, if community composition or species abundance inshore of the cages has changed as a result of reduced wave energy, then it is not clear how long it may take for the original community to recover. It is possible that some changes may be permanent.

11.1.3 Impact mitigation and management strategies

Management of current changes can be achieved through an increased understanding of structure-current interactions. Collection of data from existing structures may give information on local changes, but large-scale changes may be difficult to measure. Numerical models can provide detailed information at a range of scales but are more time consuming to set up and require greater specialist knowledge to use. However, the advantages of numerical modelling include the ability to determine optimal cage location, size, number, and cumulative effects. Modelling should be validated by field measurements where possible.

11.1.4 Knowledge gaps

The priorities for future research should be to improve knowledge of the drag on individual cages and the local effects on flow (in both vertical and horizontal directions), with and without fish, and incorporating the effects of fouling. Then, interactions between multiple cages need to be studied to provide guidance for the arrangement of larger farms. Better parameterisations of cage effects are required that can be incorporated into models to predict bay-scale or far-field effects. As discussed in the section on stratification, the effects of, and interactions with, stratification may affect currents and require investigation. But the over-riding concern is to develop physical criteria (such as minimum current speeds) based on ecological criteria relevant to the region affected.

11.2 Filter feeders (green-lipped mussels and Pacific oysters)

11.2.1 Overview of hydrodynamic effects

The production of filter feeders, such as mussels and oysters on structures suspended in the water both relies on, and influences, hydrodynamic conditions. Here, hydrodynamics refers to the physical attributes of the water including:

- currents;
- stratification;
- waves.

Stratification is the layering of water caused by differences in temperature and salinity.

Mussel farms have been shown to affect currents on local, bay-wide and regional scales. The scale of the effect depends on the size of the farms and their location. Generally, the effect is strongest within the farmed area and decreases with distance from the farm. While there has been less research on oyster farms, their influence is likely to be similar.

The main effects of suspended culture on stratification are vertical mixing and potential partial blocking of some water layers. While influences of suspended culture on stratification have been observed, they are not yet well understood. Wave energy is attenuated by suspended structures, and this will result in a shadow of reduced wave activity behind the farmed areas.

While some physical effects may influence other physical processes directly, for example, attenuation of wave energy affecting surf or coastal sediment transport, it is generally more important to consider how physical effects influence ecological processes. For example, the physical effect of reduced current speeds caused by drag from suspended culture may result in an increase in bay flushing time. This in turn may lead to increased seston or nutrient depletion. Reductions in wave energy near the coast may have significant effects on coastal habitat.

The physical hydrodynamic effects will interact strongly with pelagic and benthic processes. Selection of suitable indicators for physical changes should ideally be based on their relative importance in determining the habitat for ecological communities in an area. However, it is this link between the physical and ecological changes that is often the least understood.

11.2.2 Descriptions of main effects and their significance

11.2.2.1 Reduction in currents and redirection of flow

Table 11.4: Reduction in currents and redirection of flow due to filter-feeder aquaculture operations.

Description of effect(s)	Water speeds are reduced within farmed areas due to drag on the crop and structures. There is likely to be a reduction in tidal, wind-driven and residual current speeds over embayment scales. However, there may be local increases due to accelerations of flow around or beneath farmed areas. Bed shear stresses may be increased or decreased depending on farm layout, stocking density and water depth. Bay flushing times may be increased or decreased depending on the size and location of shellfish farms.
Spatial scale	*Local bay-wide* and *regional.*
Duration	*Short term.*
Management options	• Effects of shellfish structures on local and embayment-scale currents can be predicted using analytical and numerical models. This information can help inform ecologists and stakeholders of possible physical changes from the introduction of new structures and ways to mitigate effects. • Monitoring of currents before and during staged development could be used to ensure that effects match predictions, but care will be needed to ensure that reference sites are located beyond areas affected by the development. The duration of monitoring should be sufficient to capture a range of tide, wind and stratification conditions. These conditions should be comparable between the monitoring periods before and during development.
Knowledge gaps	• The importance of fouling is not known. Fouling will change the drag of shellfish structures. In general drag will be increased, but it is possible that, where rough surfaces are smoothed by fouling, cover drag could be decreased. • The spatial and temporal variability in currents induced by suspended structures requires more research at the small to medium (metres to hundreds of metres) scales. • More research is required on stratification, which will influence how water flows around structures. Horizontal density variations may also drive currents.

* Italicised text in this table is defined in Chapter 1 – Introduction.

Summary

Water currents are a key factor for the transport of nutrients, plankton, and larvae and for the dispersal of material. Currents near the bed will determine whether material is deposited, eroded or re-suspended. Organisms may also have habitat preferences influenced by water speed. Water currents are therefore a key driver of ecological processes.

Aquaculture structures suspended in the water are known to alter currents on a range of spatial scales. In New Zealand, mussels are grown on long-lines in 5 to 40 metre water depths, while oysters are commonly grown on racks in shallow or intertidal areas. The crop, ropes, floatation and other components of aquaculture structures are sources of flow resistance (drag). The largest consequence of this drag is a reduction of water speed within the farmed areas. Reductions in water speeds of 25 to 75 percent have been observed for a variety of structures used for aquaculture of filter feeders including rafts, long-lines, cages and piles (Blanco et al. 1996; Boyd & Heasman 1998; Plew et al. 2005; Cayocca 2006). The orientation and spacing of structures also has an important effect and can induce spatial variations in currents within farmed areas (Delaux et al. 2011).

Flow is also diverted horizontally around and/or vertically beneath the mussel farms. Diversion of flow beneath mussel farms has been measured in field experiments (Gibbs et al. 1991; Boyd & Heasman 1998; Plew et al. 2006) and studied in laboratory experiments (Plew 2011a). Increases in velocities beneath a farm may increase the shear stress on the bed, increasing the likelihood of re-suspension of sediments and deposited material (such as faeces or pseudo faeces) and affecting the depositional footprint (Giles et al. 2009). However, the effect of stratification (differences in water density caused by variations in temperature and salinity) on the diversion of flow beneath farms needs to be considered and included in models. Stratification is discussed further in Section 11.2.2.2. The increase in velocity beneath a farm also depends on farm density and the distance between the bottom of the farm structures and the bed. Analytical models suggest that velocities beneath farms are likely to be the highest when long-lines extend to around 80 percent of the water depth (Plew 2011a). Under-farm acceleration is off-set by the diversion of flow as a whole horizontally around the farm such that increases in bed shear stress of present-day New Zealand mussel farms are normally small (up to 20 percent).

There is less information on the effects of rack-grown oyster farms on currents. The magnitude of their effect on currents will depend largely on the size and spacing of the racks, and their height relative to water depth. In shallow areas, where they occupy a large fraction of the water depth, their drag will be significant, and effects are likely to be similar to mussel farms. There is a possibility of local scouring around individual piles or racks, but the net effect is likely to be a decrease in velocities. Structures will reduce currents in farmed areas, and there may be changes in topography due to deposition between the structures that will further modify currents (Nugues et al. 1996; Hewitt et al. 2006).

Drag from shellfish structures will influence tidal, wind and residual currents beyond the farm perimeters. This may lead to changes in bay flushing times and transport pathways. The horizontal diversion of flow around farmed areas can result in local increases in water speed around farms (Plew 2011b). Farms placed where currents are strong have greater drag than those in slower velocity environments. Farms placed in constricted areas, such as narrow portions of a bay, have a greater influence on flow than in wider areas as there is less room for flow to divert around the farm. It may be possible to position or dimension farms in such a way as to promote flushing of parts of a bay (Plew 2011b). This may be an option to reduce the risk of seston depletion (Gibbs 2007; Plew 2011b).

Overseas experience shows that, if suspended aquaculture covers the majority of a bay, currents are significantly reduced throughout the bay, including within navigation channels left between crops (Grant & Bacher 2001; Shi et al. 2011). Currently, in New Zealand, aquaculture is less intensive, typically occupying up to 10 percent of a bay area in enclosed waters, such as in the Marlborough Sounds. Modelling of tidal currents shows that this less intensive approach to farming still has effects on current speeds that can extend over the whole bay or beyond (Plew 2011b). The magnitude of the effect of farms depends on the farm location, stocking density and the depth to which the structures extend. The effects of farms on hydrodynamics will be cumulative, but the effect of individual farms will not necessarily be equal.

In addition to the physical and ecological consequences of the effect of aquaculture structures on currents, current speeds also have an influence on the structures. Forces on moorings and structural components are increased by strong currents, placing greater emphasis on engineering design to prevent damage to or loss of the crop and structure.

Farm-scale changes in currents are almost certain. Embayment-scale changes in circulation are highly likely in small bays or with large farms. The physical effects on currents will persist for the duration that the structures and crop are in place. Return to ambient conditions on removal of all structures will be nearly immediate. Ecological consequences of modified currents may persist for longer. For example, if the composition of ecological communities or the abundance of species has altered as a result of changes to currents, recovery from these changes could be slow. It is possible that some changes could be permanent.

11.2.2.2 Stratification

Table 11.5: Effects on stratification due to filter-feeder aquaculture operations.

Description of effect(s)	Stratification is the layering of water bodies due to differences in density as a consequence of temperature and salinity. Aquaculture structures are not likely to directly affect salinity, but there is a theoretical possibility of a small influence on temperature. Suspended aquaculture structures alter stratified water bodies through: • blocking or diversion of some water layers; • generation of internal waves; • possible enhancement of vertical mixing.
Spatial scale	*Local* and *bay-wide.*
Duration	*Short term.*
Management options	• Site selection criteria to be set in conjunction with ecological issues relating to hydrodynamics, for example, benthic deposition and pelagic effects. • Monitoring of temperature and salinity profiles.
Knowledge gaps	• It is not known if changes in water clarity caused by removal or addition of suspended or dissolved material have a significant influence on temperature through absorption of solar energy. • The magnitude and spatial scales of changes to stratification need to be better understood in order to determine any ecological consequences. • The interactions between stratified flows and suspended structures are poorly understood. More research is required to understand: – how stratification affects the diversion of flow beneath or around a farm; – whether the structures induce significant vertical mixing; – if shellfish farms can be designed to change vertical mixing.

* Italicised text in this table is defined in Chapter 1 – Introduction.

Summary

The density of water is primarily determined by salinity and temperature. Less dense water (warmer or fresher) tends to rise and lie over more dense (saltier or colder) water, this is termed stratification. Stratification is important ecologically as temperature and salinity can be a factor in pelagic and benthic habitat suitability for organisms or communities (Abookire et al. 2000; McLeod & Wing 2008). Oceanic and coastal waters are nearly always stratified to some degree due to the effects of river inflow, mixing of different water bodies and heating and cooling. The degree of stratification may vary on daily to seasonal time scales. Longer term climate conditions (e.g. El Niño/La Niña-Southern Oscillation) will also influence stratification.

Water temperature is primarily driven by heat exchange with the atmosphere, absorption of solar radiation and radiated losses from the surface. Other causes of temperature variations are river inflows or transport and mixing of waters from oceanic sources. There is a theoretical potential for shellfish to increase water temperature through the dissipation of turbulence, but this is expected to be insignificant and likely to be below detection limits. Shells and structures may be warmed by solar radiation and, in turn, heat the surrounding water. Only objects exposed to sunlight are likely to be heated. It is not known if there is any detectable heating resulting from sunlight on the shells and structure.

There is also potential for changes in solar heating due to changes in water clarity. The depth of light penetration into the water column depends on various optical properties of the water, including the concentration, size and nature of suspended and dissolved material. These could be changed through filter feeding and production of faeces and pseudo faeces. Additional removal or production of suspended or dissolved material may result from biofouling. High release of suspended material may occur during seeding, thinning or harvesting operations or due to wave action. Improvements in water clarity have been measured inside mussel long-line farms in Denmark where the water is highly eutrophic (J. Petersen, pers. comm.). Reductions in acoustic backscatter intensity and increased optical transmissivity have been observed in New Zealand and Denmark (D. Plew, P. Cranford pers. comm.). There may also be direct shading caused by the crop and structure.

Shellfish are unlikely to have a direct effect on salinity as they neither consume nor produce salt.

The most likely cause of changes in salinity and temperature distributions will be through altering currents as described in Section 11.2.2.1 and through enhanced vertical mixing

Field observations have shown that mussel farm structures interact with stratification, resulting in changes in the depth of iso pycnals (surfaces of constant density as described in 11.1.2.2) (Plew et al. 2005; Plew et al. 2006). Preliminary laboratory experiments indicate that strong stratification will resist vertical diversion beneath farms. Consequently, stratification needs to be considered alongside flow diversion. Laboratory experiments also indicate that internal waves can be produced when stratified water moves past a porous obstruction, such as suspended shellfish structures. These internal waves propagate away from the farm. It is not yet clear whether shellfish long-lines or cages generate significant vertical mixing, although the degree of mixing will also depend on the strength of the stratification relative to water velocities. Strong stratification resists vertical mixing.

The influence of stratification depends on how great the differences in water density are and the strength of other physical processes that drive water motion, such as tides and weather. The spatial scale of the effect of shellfish structures on stratification is unknown. Blocking and diversion will be most apparent within and near the farms. Internal waves may travel a considerable distances. Mixing is most likely to occur within and immediately downstream of the structures. However, this mixed water will be transported by currents, and the effect may become more pronounced over several tidal cycles as water is repeatedly advected through structures.

Little is known about the effect of oyster racks on stratification. In general, these structures are placed in shallow or intertidal areas where the water column is likely to be well mixed. However, estuarine environments can still be stratified. Oyster racks in these environments are highly likely to increase vertical mixing.

Coastal environments experience a range of salinity and temperatures, and it is difficult to predict if changes in stratification will have significant ecological effects without first understanding the magnitude and spatial scales of these changes. The physical effects on stratification will persist for the duration that the structures and crop are in place. Return to ambient conditions on removal of all structures will depend on the length of time that water is replaced within the embayment but is likely to be less than a year. Ecological consequences of changes to stratification may persist for longer. For example, if the composition of ecological communities or the abundance of species has altered as a result of the effects of shellfish farm structures on stratification, it is not clear how long recovery to the original community condition may take. It is possible that some changes may be irreversible.

11.2.2.3 Wave dampening

Table 11.6: Effects of wave dampening due to filter-feeder aquaculture operations.

Description of effect(s)	• Wave energy is attenuated due to the wave drag on the suspended crop, floatation and structural components. • A wave shadow of reduced wave energy will extend down-wave of the farmed areas. • Reduced wave energy may affect shoreline habitat and sediment transport.
Spatial scale	*Bay-wide* to *regional.*
Duration	*Short term.*
Management options	• Prediction of wave attenuation using analytical or numerical methods. • Monitoring of wave attenuation during staged development. • Thresholds for acceptable wave attenuation could be set to protect ecological communities. • Wave attenuation could be reduced using alternative designs, where the bulk of the crop and structure are submerged.
Knowledge gaps	More measurements of wave attenuation by shellfish aquaculture are required to develop and validate predictive models. There is also a lack of knowledge of: • the effect of the orientation of long-lines to the direction of wave travel; • whether different long-line stocking densities or designs significantly alter wave attenuation; • if refraction (changes in the direction of wave propagation) or reflection of waves occurs; • if the motion or flexibility of long-line structures lead to greater attenuation of waves of particular periods; • the effect of wave height on wave attenuation.

* Italicised text in this table is defined in Chapter 1 – Introduction.

Summary

The environmental significance of farm-induced wave attenuation includes possible changes to sediment transport, beach erosion and replenishment and changes in habitat for species that have acclimatised to wave conditions. In addition, as waves can induce significant structural force, there is a risk of debris from damaged long-lines or racks during storm events.

Structures placed in the water can act as dissipaters of wave energy. Wave energy is lost due to friction of the wave-induced water motion against the crop and support structures. To date, measurements of wave energy attenuation by long-line mussel farms have only been made at a few sites. Measurements at one of New Zealand's largest mussel farms presently in operation found reductions in wave energy of 5 to 20 percent (Plew et al. 2005). While these measurements are specific to this farm and the conditions at the time of measurement, it shows that wave attenuation from mussel farms can be measurable.

For mussel long-lines supported from the surface, the amount of wave energy lost varies with wave period, with more energy lost from short period waves, such as wind chop, and less from longer period waves such as ocean swell (Plew et al. 2005). The loss in wave energy is likely to depend on the stocking density and the size of farm. Wave attenuation may also increase with wave height (Plew et al. 2005), although more data is required to confirm this. The horizontal water excursion beneath a wave decreases with depth below the surface. Waves penetrate to a depth of half of their wave length. Consequently, most of the energy loss occurs near the surface, particularly for short period waves. Wave attenuation could be reduced using alternative designs where the bulk of the crop and structure are submerged. This will be particularly effective for short period waves.

Wave attenuation will manifest as a shadow of reduced wave heights extending down-wave from the farm. The farm-wave shadow will be of limited size as wave energy will refract horizontally from regions not influenced from the farm.

The observed reduction in wave height will decrease with distance from the farm. There is currently no guidance on the size of any wave shadow or how this will relate to farm dimensions, stocking density, farm and long-line design and water depth.

At present, an analytical model is used to predict wave attenuation, which does compare well with the available field data (Plew et al. 2005). However, this model needs to be validated against data from more locations and a wider range of conditions and modified if necessary.

In addition to the direct effect of structures, deposition beneath farmed areas may change water depth, which could potentially cause wave shoaling and refraction (Nugues et al. 1996; Hewitt et al. 2006; Forrest et al. 2009).

The environmental significance of farm-induced wave attenuation includes possible changes to sediment transport, beach erosion and replenishment and changes in habitat for species that have acclimatised to wave conditions. Longer period and large amplitude waves that reach the seabed beneath farms may re-suspend deposited shell or faecal material during storm events (Hartstein & Stevens 2005).

Some degree of wave attenuation will occur for any shellfish structure with surface or near surface components. The effect may be undetectable for small farms or in sheltered areas. The physical effects on waves will persist for the duration that the structures and crop are in place. Return to ambient conditions on removal of all structures will be nearly immediate. Ecological consequences of modified wave climate may persist for longer. For example, if community composition or species abundance inshore of the cages has changed as a result of reduced wave energy, it is not clear how long it may take for the original community to recover. It is possible that some changes may be irreversible.

11.2.3 Impact mitigation and management strategies

See Section 11.1.3.

11.2.4 Knowledge gaps

The priorities for future research include improving knowledge of flow modification at the farm and long-line scale, and the spatial variations in currents and bed shear stress within farms. More research is required relating long-line spacing and orientation to three-dimensional flow fields (especially vertical diversion) and far field effects. Improved understanding is also needed of how much stratification affects the diversion of flow beneath or around farms, and how far from farms these effects extend. This research could also be conducted to determine if vertical mixing is enhanced or decreased, and under what conditions this occurs.

Studies could determine if there are sufficient changes in water clarity caused by removal or addition of suspended or dissolved material, to have an impact water temperature through absorption of solar energy.

More measurements are needed of wave attenuation to test existing models for wave attenuation. Research on the effects of long-line or rack design and orientation, as well as wave reflection and refraction, will provide a basis for improving models of wave attenuation. The over-riding concern is to develop physical criteria (such as acceptable changes in current speeds) based on ecological criteria. With the establishment of ecologically based criteria, such models could then be used as tools to determine acceptable farm size and density.

11.3 Lower trophic level species

11.3.1 Overview of hydrodynamic strategies

The hydrodynamic effects relevant to aquaculture of lower trophic level organisms depends mostly on whether they are grown in a suspended culture, such as *Undaria*, or on the sea bed. Here, hydrodynamics refers to the physical attributes of the water including:

- currents;
- stratification;
- waves.

Stratification is the layering of water caused by differences in temperature and salinity.

Suspended culture, such as long-lines of *Undaria*, will have similar hydrodynamic effects to other suspended aquaculture activities like mussel long-lines and fish cages. Suspended culture has been shown to affect currents on local, bay-wide and regional scales. Generally, the effect is strongest within the farmed area and decreases with distance from the farm. The main effects of suspended culture on stratification are vertical mixing and potential partial blocking of some water layers. While influences of suspended culture on stratification have been observed, these interactions are not yet well understood. Wave energy is attenuated by suspended structures, and this will result in a shadow of reduced wave activity behind the farmed areas. These modifications to the physical environmental will need to be accounted for when determining the suitability of a site to support an aquaculture activity, as well as its effects on the environment.

Aquaculture conducted on the seafloor is likely to have effects that differ depending upon the need for structures. The hydrodynamic issues related to structures on the sea floor (such as cages, nets, sticks or posts) will depend on the water depth and how much of the water column is occupied. In shallow areas or where the structures extend over a large portion of the water column, the effects on currents, waves and stratification may be similar to that of suspended structures. Aquaculture conducted directly on the sea floor is likely to have smaller effects.

Water velocities, wave exposure, temperature and salinity will need to be within suitable ranges for the cultured organism. The effects of the aquaculture on hydrodynamics are likely to be restricted to changes in bottom friction and possibly water clarity. The effects of bottom culture on currents, waves and stratification will be greatest in shallow areas and are likely to be least in deeper water.

While some physical effects may influence other physical processes directly, for example, attenuation of wave energy affecting surf or coastal sediment transport, it is generally more important to consider how physical effects influence ecological processes. For example, the physical effect of reduced current speeds caused by drag from suspended culture, or increased bottom friction from bottom culture, may result in an increase in bay flushing time. This in turn may lead to increased nutrient concentrations or depletion.

Reductions in wave energy near the coast may have significant effects on coastal habitat (Harris 2009; Smith et al. 2009).

The physical hydrodynamic effects will interact strongly with pelagic and benthic processes. Selection of suitable indicators for physical changes should ideally be based on their relative importance in determining the habitat for ecological communities in an area. However, it is this link between the physical and ecological changes that is often the least understood.

11.3.2 Descriptions of main effects and their significance

11.3.2.1 Reduction in currents and redirection of flow

Table 11.7: Reduction in currents and redirection of flow due to lower trophic level aquaculture operations.

Description of effect(s)	Water speeds are reduced within areas used for suspended culture due to drag on the crop and structures. Bed shear stresses may be increased or decreased depending on farm layout, stocking density, porosity and water depth. Benthic aquaculture may increase bottom roughness, particularly if structures or enclosures are used, leading to reductions in near-bed current speeds. There is likely to be a reduction in tidal, wind-driven and residual current speeds over embayment scales. However, there may be local increases due to accelerations of flow around or beneath farmed areas. Bay flushing times may be increased or decreased depending on the size and location of farms.
Spatial scale	*Local*, *bay-wide,* and *regional.*
Duration	*Short term.*
Management options	• Effects of benthic or suspended structures on local and embayment-scale currents can be predicted using analytical and numerical models. This information can help inform ecologists and stakeholders of possible physical changes from the introduction of new structures or aquaculture activities and of ways to mitigate effects. • Monitoring of currents before and during staged development could be used to ensure effects match predictions, but care will be needed to ensure that reference sites are located beyond areas affected by the development. The duration of monitoring should be sufficient to capture a range of tide, wind and stratification conditions. These conditions should be comparable between the before and during monitoring periods.
Knowledge gaps	There is a lack of information on: • the types of structures or enclosures that might be used for bottom culture; • how much bottom roughness might be changed by benthic aquaculture; • how stratification will influence how water flows around suspended structures and how induced changes in horizontal density variations may affect currents; • ecological responses to changes in currents.

* Italicised text in this table is defined in Chapter 1 – Introduction.

Summary

Water currents are a key factor for transport of nutrients, plankton, larvae and for dispersal of material. Currents near the bed will determine whether material is deposited, eroded or re-suspended. Organisms may also have habitat preferences influenced by water speed. Water currents are therefore a key driver of ecological processes.

Aquaculture structures suspended in the water are known to alter currents on a range of spatial scales. The crop, ropes, floatation and other components of suspended aquaculture structures are sources of flow resistance (drag). The largest consequence of this drag is a reduction of water speed within the farmed areas. Reductions in water speeds of 25 to 75 percent have been observed for a variety of structures used for aquaculture including rafts, long-lines, cages and piles (Blanco et al. 1996; Boyd & Heasman 1998; Plew et al. 2005; Cayocca 2006; Shi et al. 2011). The orientation and spacing of structures also has an important effect and can induce spatial variations in currents within farmed areas (Delaux et al. 2011).

Flow is also diverted horizontally around and/or vertically beneath suspended aquaculture. Diversion of flow beneath aquaculture structures has been measured in field experiments (Gibbs et al. 1991; Boyd & Heasman 1998; Plew et al. 2006) and studied in depth in laboratory experiments (Plew 2011a). Increases in velocities beneath structures may increase the shear stress on the bed, increasing the likelihood of re-suspension of sediments. However, the effect of density stratification on the diversion of flow beneath structures needs to be considered and included in models. Stratification is discussed further in Section 11.2.2.2. The increase in velocity beneath a structure also depends on the porosity of the structure (determined by crop size, spacing and layout) and distance between the bottom of the structures and the bed. Analytical models suggest that velocities beneath farmed areas are likely to be highest when crops extend to around 80 percent of the water depth (Plew 2011a).

The effect of benthic culture will depend largely on whether any form of structure or enclosure is used to contain the crop (Chew 1984; Slater & Carton 2007; Forrest et al. 2009; Smith & McDonald 2009). Structures on the sea bed will increase flow resistance, generate turbulence, and may increase the boundary layer thickness. There is a possibility of local scouring around individual piles or cages, but the net effect is likely to be a decrease in velocities near the bed. Structures will reduce currents in farmed areas, and there may be changes in topography due to deposition between the structures, which will further modify currents (Nugues et al. 1996; Hewitt et al. 2006). Enclosures or cages may not be required to retain some species, such as sea cucumber, if the availability of organic matter is sufficient (Slater & Carton 2007). However, any substrate or rock piles used to create a refuge will increase flow resistance to some degree. Effects on currents are likely to be greatest for suspended structures, followed by bottom structures, un-enclosed with benthic organisms likely to have the smallest effects on currents.

The likely effects also depend on the type of organism cultivated. For example, measurements show that benthic mussels alter the benthic boundary layer (Nikora et al. 2002). Shear velocities and bed shear stress are increased when mussels are open and feeding compared with when they are closed, with exhalent jets acting as additional roughness elements, increasing drag (Van Duren et al. 2006). Similar effects might be expected for other shellfish growing in or on the bed, in addition to the physical flow resistance from the shells. Grazers, such as sea cucumbers, are unlikely to modify flow directly but may alter bed roughness by moving or disturbing material. Other changes to bottom roughness may occur from harvesting operations if these require digging, dredging or burrowing (Dumbauld et al. 2009). The effect of benthic structures or organisms on currents will be greatest in shallow sites.

Drag from suspended or benthic aquaculture structures will influence tidal, wind and residual currents beyond the farm perimeters. This may lead to changes in bay flushing times and transport pathways. The horizontal diversion of flow around farmed areas can result in local increases in water speed around farms (Plew 2011b). Farms placed where currents are strong have greater drag than those in slower velocity environments. Farms placed in constricted areas, such as narrow portions of a bay, have a greater influence on flow than in wider areas as there is less room for flow to divert around the farm. It may be possible to position or dimension farms in such a way as to promote flushing of parts of a bay (Plew 2011b).

Overseas experience shows that, if suspended aquaculture covers the majority of a bay, currents are significantly reduced throughout bay, including within navigation channels left between crops (Grant & Bacher 2001; Shi et al. 2011). Currently, in New Zealand, aquaculture is less intensive, typically occupying up to 10 percent of a bay area in enclosed waters, such as in the Marlborough Sounds. Modelling of tidal currents shows that this less intensive approach to farming still has effects on current speeds that can extend over the whole bay or beyond (Plew 2011b). The magnitude of the effect of farms depends on the farm location, stocking density and the depth to which the structures extend. The effects of farms on hydrodynamics will be cumulative, but the effect of individual farms will not necessarily equal.

In addition to the physical and ecological consequences of the effect of aquaculture structures on currents, current speeds also have an influence on the structures. Forces on moorings and structural components are increased by strong currents, placing greater emphasis on engineering design to prevent damage to or loss of the crop and structure.

Local farm-scale changes in currents are almost certain. Embayment-scale changes in circulation are highly likely in small bays or with large farms. The physical effects on currents will persist for the duration that the structures and crop are in place. Return to ambient conditions on removal of all structures will be nearly immediate. However, alteration to bed roughness caused by the activity of benthic feeders or harvesting of bottom culture may take longer to recover. Ecological consequences of modified currents may persist for longer. For example, if the composition of ecological communities or the abundance of species has altered as a result of changes to currents, recovery from these changes could be slow, or some changes could possibly be permanent.

Management of current changes can be achieved through an increased understanding of structure current interactions. Collection of data from existing structures may give information on local changes, but large-scale changes may be difficult to measure. Numerical models can provide more detailed information but are more time consuming and require greater specialist knowledge to use. However, the advantages of numerical modelling include the ability to determine optimal farm location and size and cumulative effects. Modelling should be validated by field measurements where possible.

11.3.2.2 Stratification

Table 11.8: Effects on stratification due to lower trophic level aquaculture operations.

Description of effect(s)	Stratification is the layering of water bodies due to differences in density as a consequence of temperature and salinity. Aquaculture structures are not likely to directly affect salinity but there is a theoretical possibility of a small influence on temperature. Suspended aquaculture structures alter stratified water bodies through: • blocking or diversion of some water layers; • generation of internal waves; • possible enhancement of vertical mixing. Benthic aquaculture may increase vertical mixing.
Spatial scale	*Local* and *bay-wide.*
Duration	*Short term.*
Management options	• Site selection criteria to be set in conjunction with ecological issues relating to hydrodynamics, for example, benthic or pelagic effects. • Monitoring of temperature, salinity and oxygen profiles.
Knowledge gaps	The interactions between stratified flows and suspended structures are poorly understood. More research is required to understand: • how stratification affects the diversion of flow beneath or around a farm; • whether the structures induce significant vertical mixing; • if structures can be designed to change vertical mixing. It is not known whether changes in water clarity, caused by the removal or addition of suspended or dissolved material, have a significant influence on temperature through absorption of solar energy. The magnitude and spatial scales of changes to stratification need to be better understood in order to determine any ecological consequences.

* Italicised text in this table is defined in Chapter 1 – Introduction.

Summary

The density of water is primarily determined by salinity and temperature. Less dense water (warmer or fresher) tends to rise and lie over more dense (salter or colder) water. Stratification is important ecologically as temperature and salinity can be a factor in pelagic and benthic habitat suitability for organisms or communities (Abookire et al. 2000; McLeod & Wing 2008). Oceanic and coastal waters are nearly always stratified to some degree due to the effects of river inflow, mixing of different water bodies and heating and cooling. The degree of stratification may vary on daily to seasonal time scales. Longer term climate conditions (e.g. El Niño/La Niña-Southern Oscillation) will also influence stratification.

Water temperature is primarily driven by heat exchange with the atmosphere, absorption of solar radiation and radiated losses from the surface. Other causes of temperature variations are river inflows or transport and mixing of waters from oceanic sources. There is a theoretical potential for suspended or benthic culture to increase water temperature through the dissipation of turbulence, but this is expected to be insignificant and likely to be below detection limits. Suspended or shallow benthic culture may be warmed by solar radiation and, in turn, heat surrounding water. Only objects exposed to sunlight are likely to be heated.

There is also potential for changes in solar heating due to changes in water clarity. The depth of light penetration into the water column depends on various optical properties of the water, including the concentration, size and nature of suspended and dissolved material. There may also be direct shading caused by crops and structures.

The most likely cause of changes in salinity and temperature distributions will be through altering currents, as described in 11.2.2.1, and through enhanced vertical mixing

Field observations have shown that suspended culture interacts with stratification, resulting in changes in the depth of isopcynals (surfaces of constant density as described in 11.1.2.2) (Plew et al. 2005; Plew et al. 2006). Preliminary laboratory experiments indicate that strong stratification will resist vertical diversion beneath porous structures. Consequently, stratification needs to be considered alongside flow diversion. Laboratory experiments also indicate that internal waves can be produced when stratified water moves past a porous obstruction, such as suspended aquaculture structures. These internal waves propagate away from the farm. It is not yet clear whether suspended culture generates significant vertical mixing, although the degree of mixing will also depend on the strength of the stratification relative to water velocities because strong stratification resists vertical mixing.

The main effect of benthic culture is an increase in boundary layer turbulence, and potentially an increase in boundary layer thickness (Nikora et al. 2002; van Duren et al. 2006). This may lead to increased vertical mixing, however, the effect is likely to be small in deep water. Suspended sediments can also affect stratification, and activities that re-suspend sediments have the potential to alter density, particularly near the bed. This could lead to weak turbidity currents that are likely to propagate down-slope (Kneller & Buckee 2000).

The influence of stratification depends on how great the differences in water density are and the strength of other physical processes that drive water motion, such as tides and weather. The spatial scale of the effect of suspended aquaculture structures on stratification is unknown. Blocking and diversion will be most apparent within and near the farms. Internal waves may travel a considerable distance. Mixing is most likely to occur within and immediately downstream of the structures. However, this mixed water will be transported by currents, and the effect may become more pronounced over several tidal cycles if water is repeatedly by advected back through structures. Stratification will also influence the dispersal and dilution of dissolved products, including ammonia. In a strongly stratified environment, dissolved material will remain above or below the pycnocline (the depth of greatest change in water density with depth) depending on its source depth.

Coastal environments experience a range of salinity and temperatures, and it is difficult to predict whether changes in stratification will have significant ecological effects without first understanding the magnitude and spatial scales of these changes. The physical effects on stratification will persist for the duration that the structures and crop are in place. Return to ambient conditions on removal of all structures will depend on the length of time that water is replaced within the embayment, but is expected to be less than a year. Ecological consequences of changes to stratification may persist for longer. For example, if the composition of ecological communities or the abundance of species has altered as a result of the effects of farm structures on stratification, it is not clear how long recovery to the original community condition may take. It is possible that some changes may be irreversible.

11.3.2.3 Wave dampening

Table 11.9: Effects of wave dampening due to lower trophic level aquaculture operations.

Description of effect(s)	• Wave energy is attenuated due to the wave drag on suspended crop, floatation and structural components. • A wave shadow of reduced wave energy will extend down-wave of the farmed areas. • Increased bottom roughness due to benthic culture may also cause wave attenuation, particularly if structures or enclosures are used. Wave attenuation from bottom culture will be greatest in shallow water. • Reduced wave energy may affect shoreline habitat and sediment transport.
Spatial scale	*Bay-wide* to *regional.*
Duration	*Short term.*
Management options	• Predictions of wave attenuation using analytical or numerical models. • Monitoring of wave attenuation during staged development. • Thresholds for acceptable wave attenuation could be set to protect ecological communities. • Wave attenuation or reflection could be reduced by manipulating the design, flexibility or porosity of structures.
Knowledge gaps	More measurements of wave attenuation by both benthic and suspended aquaculture are required to develop and validate predictive models. There is also a lack of knowledge of: • the effect of the orientation of long-lines for suspended culture to the direction of wave travel; • whether different stocking densities or designs significantly alter wave attenuation; • if refraction (changes in the direction of wave propagation) or reflection of waves occurs; • how the motion or flexibility of structures lead to greater attenuation of waves of particular periods; • the effect on wave height on wave attenuation; • how much bottom roughness could be changed by benthic aquaculture; • the types of structures or enclosures that might be used for benthic aquaculture.

* Italicised text in this table is defined in Chapter 1 – Introduction.

Summary

The environmental significance of farm-induced wave attenuation includes possible changes to sediment transport, beach erosion and replenishment, and changes in habitat for species that have acclimatised to wave conditions.

Structures placed in the water can act as dissipaters of wave energy. Wave energy is lost due to friction of the wave-induced water-motion against the crop and support structures. There are observational accounts of reduced wave energy within suspended culture (Grant & Bacher 2001; Plew et al. 2005). For long-lines supported from the surface, the amount of wave energy lost varies with wave period, with more energy lost from short period waves, such as wind chop, and less from longer period waves such as ocean swell (Plew et al. 2005). The loss in wave energy is likely to depend on the stocking density and size of farm. Wave attenuation may also increase with wave height (Plew et al. 2005), although more data is required to confirm this.

Wave energy may be reflected as well as attenuated. Studies of floating cage breakwaters show that reflection normally accounts for the majority of the reduction in wave transmission (Massel 1976; Yu 1995). However, more flexible buoyant structures offer far greater dissipation with very little reflection (Seymour & Hanes 1979; Williams & McDougal 1996). Analogy can also be made to other floating structures, such as kelp forests (Dalrymple et al. 1984; Asano et al. 1988; Kobayashi et al. 1993) which also can attenuate wave energy.

The horizontal water movement beneath a wave decreases with depth below the surface. Waves penetrate to a depth of half of their wave length. Consequently, most of the energy loss for waves travelling through suspended aquaculture occurs near the surface, particularly for short period waves. Wave attenuation could be reduced using alternative designs where the bulk of the crop and structure are submerged. This will be particularly effective for reducing effects upon short period waves.

Benthic culture may result in an increase in bottom roughness, particularly if structures or enclosures are used. Increased bottom roughness may also increase wave attenuation. Attenuation will only occur for waves with wave lengths longer than about twice the water depth. Attenuation from bottom culture will therefore be greatest for longer period waves, and increase as the water depth shallows.

Wave attenuation will manifest as a shadow of reduced wave heights extending down-wave from the farm. The farm-wave shadow will be of limited size as wave energy will refract horizontally from regions not influenced from the farm. The observed reduction in wave height will decrease with distance from the farm. There is currently no guidance on the size of any wave shadow, or how this will relate to farm dimensions, stocking density, farm and long-line design and water depth.

At present, an analytical model is used to predict wave attenuation for long-line mussel farms (Plew et al. 2005), and this could be adapted for other forms of suspended culture. However, this model needs to be validated against data from more locations and a wider range of conditions and modified if necessary. Further work is required to evaluate and parameterise any increase in bottom roughness caused by benthic aquaculture.

The environmental significance of farm-induced wave attenuation includes possible changes to sediment transport, beach erosion and replenishment, and changes in habitat for species that have acclimatised to wave conditions.

Some degree of wave attenuation will occur for any suspended aquaculture structure with surface or near surface components. The effect may be undetectable for small farms or in sheltered areas. The physical effects on waves will persist for the duration that the structures and crop are in place. Return to ambient conditions on removal of all structures will be nearly immediate. Ecological consequences of modified wave climate may persist for longer. For example, if community composition or species abundance inshore of the cages has changed as a result of reduced wave energy, then it is not clear how long it may take for the original community to recover. It is possible that some changes could be irreversible.

11.3.3 Impact mitigation and management strategies

See Section 11.1.3.

11.3.4 Knowledge gaps

See Section 11.2.4.

References

Abookire, A.A.; Piatt, J.F.; Robards, M.D. (2000). Nearshore fish distributions in an Alaskan estuary in relation to stratification, temperature and salinity. *Estuarine, Coastal and Shelf Science 51*: 45–59.

Asano, T.; Tsutsui, S.; Sakai, T. (1988). *Wave damping characteristics due to seaweed*. 35th Coastal Engineering Conference in Japan. Japan Society of Civil Engineers.

Beveridge, M.C.M. (2004). *Cage aquaculture* (3rd edn.). Blackwell Publishing, Oxford, United Kingdom.

Black, K.D.; Hansen, P.K.; Holmer, M. (2008). *Salmon Aquaculture Dialogue: Working Group Report on Benthic Impacts and Farm Siting*. Salmon Aquaculture Dialogue, World Wildlife Fund, Washington, DC, United States of America. www.worldwildlife.org/what/globalmarkets/aquaculture/WWFBinaryitem8841.pdf. Accessed March 2012.

Blanco, J.; Zapata, M.; Moroño, Á. (1996). Some aspects of the water flow through mussel rafts. *Scientia Marina 60*: 275–282.

Boyd, A.J.; Heasman, K.G. (1998). Shellfish mariculture in the Benguela system: Water flow patterns within a mussel farm in Saldanha Bay, South Africa. *Journal of Shellfish Research 17*: 25–32.

Cayocca, F. (2006). Morphological evolutions of a macrotidal bay under natural conditions and anthropogenic modifications. In: *River, Coastal and Estuarine Morphodynamics: RCEM 2005*. Proceedings of the 4th IAHR Symposium on River, Coastal and Estuarine Morphodynamics (RCEM 2005, Urbana, Illinois, USA, 4–7 October). Parker, G.; Garcia, M.H. (eds.). Taylor & Francis Group, London, United Kingdom.

Chacon-Torres, A.; Ross, L.G.; Beveridge, M.C.M. (1988). The effects of fish behaviour on dye dispersion and water exchange in small net cages. *Aquaculture 73*: 283–293.

Chan, A.T.; Lee, S.W.C. (2001). Wave characteristics past a flexible fishnet. *Ocean Engineering 28*: 1517–1529.

Chew, K.K. (1984). Recent advances in the cultivation of molluscs in the Pacific United States and Canada. *Aquaculture 39*: 69–81.

Dalrymple, R.A.; Kirby, J.T.; Hwang, P.A. (1984). Wave diffraction due to areas of energy dissipation. *Journal of Waterway, Port, Coastal and Ocean Engineering 110*: 67–79.

Delaux, S.; Stevens, C.L.; Popinet, S. (2011). High-resolution computational fluid dynamics modelling of suspended shellfish structures. *Environmental Fluid Mechanics 11*: 405–425.

Dumbauld, B.R.; Ruesink, J.L.; Rumrill, S.S. (2009). The ecological role of bivalve shellfish aquaculture in the estuarine environment: A review with application to oyster and clam culture in West Coast (USA) estuaries. *Aquaculture 290*: 196–223.

Forrest, B.M.; Keeley, N.B.; Hopkins, G.A.; Webb, S.C.; Clement, D.M. (2009). Bivalve aquaculture in estuaries: Review and synthesis of oyster cultivation effects. *Aquaculture 298*: 1–15.

Gibbs, M.M.; James, M.R.; Pickmere, S.E.; Woods, P.H.; Shakespeare, B.S.; Hickman, R.W.; Illingworth, J. (1991). Hydrodynamic and water column properties at six stations associated with mussel farming in Pelorus Sound, 1984–85. *New Zealand Journal of Marine and Freshwater Research 25*: 239–254.

Gibbs, M.T. (2007). Sustainability performance indicators for suspended bivalve aquaculture activities. *Ecological Indicators 7*: 94–107.

Giles, H.; Broekhuizen, N.; Bryan, K.R.; Pilditch, C.A. (2009). Modelling the dispersal of biodeposits from mussel farms: The importance of simulating biodeposit erosion and decay. *Aquaculture 291*: 168–178.

Grant, J.; Bacher, C. (2001). A numerical model of flow modification induced by suspended aquaculture in a Chinese bay. *Canadian Journal of Fisheries and Aquatic Sciences 58*: 1003–1011.

Harris, L. (2009). Artificial reefs for ecosystem restoration and coastal erosion protection with aquaculture and recreational amenities. *REEF Journal 1*: 235–246.

Hartstein, N.D.; Stevens, C.L. (2005). Deposition beneath long-line mussel farms. *Aquacultural Engineering 33*: 192–213.

Helsley, C.E.; Kim, J.W. (2005). Mixing downstream of a submerged fish cage: A numerical study. *IEEE Journal of Oceanic Engineering 30*: 12–19.

Hewitt, J.; Morrison, M.; Spigel, R.; Turner, S. (2006). *Oyster farming in the Kaipara Harbour proposed aquaculture management area D, Ecological Assessment*. NIWA Client Report HAM2006-118.

Johansson, D.; Juell, J.E.; Oppedal, F.; Stiansen, J.E.; Ruohonen, K. (2007). The influence of the pycnocline and cage resistance on current flow, oxygen flux and swimming behaviour of Atlantic salmon (*Salmo salar* L.) in production cages. *Aquaculture 265*: 271–287.

Johansson, D.; Ruohonen, K.; Kiessling, A.; Oppedal, F.; Stiansen, J.E.; Kelly, M.; Juell, J.E. (2006). Effect of environmental factors on swimming depth preferences of Atlantic salmon (*Salmo salar* L.) and temporal and spatial variations in oxygen levels in sea cages at a fjord site. *Aquaculture 254*: 594–605.

Kneller, B.; Buckee, C. (2000). The structure and fluid mechanics of turbidity currents: A review of some recent studies and their geological implications. *Sedimentology 47*: 62–94.

Kobayashi, N.; Raichle, A.; Asano, T. (1993). Wave attenuation by vegetation. *Journal of Waterway, Port, Coastal and Ocean Engineering 119*: 30–48.

Lader, P.F.; Olsen, A.; Jensen, A.; Sveen, J.K.; Fredheim, A.; Enerhaug, B. (2007). Experimental investigation of the interaction between waves and net structures—Damping mechanism. *Aquacultural Engineering 37*: 100–114.

Mantzavrakos, E.; Kornaros, M.; Lyberatos, G.; Kaspiris, P. (2007). Impacts of a marine fish farm in Argolikos Gulf (Greece) on the water column and the sediment. *Desalination 210*: 110–124.

Massel, S.R. (1976). Interaction of water waves with cylindrical barrier. *Journal of Waterway, Port, Coastal and Ocean Engineering 102*: 162–187.

McLeod, R.J.; Wing, S.R. (2008). Influence of an altered salinity regime on the population structure of two infaunal bivalve species. *Estuarine, Coastal and Shelf Science 78*: 529–540.

Merceron, M.; Kempf, M.; Bentley, D.; Gaffet, J.D.; Le Grand, J.; Lamort-Datin, L. (2002). Environmental impact of a salmonid farm on a well flushed marine site: I. Current and water quality. *Journal of Applied Ichthyology 18*: 40–50.

Nikora, V.; Green, M.O.; Thrush, S.F.; Hume, T.M.; Goring, D. (2002). Structure of the internal boundary layer over a patch of pinnid bivalves (*Altrina zelandica*) in an estuary. *Journal of Marine Research 60*: 121–150.

Nugues, M.M.; Kaiser, M.J.; Spencer, B.E.; Edwards, D.B. (1996). Benthic community changes associated with intertidal oyster cultivation. *Aquaculture Research 27*: 913–924.

Plew, D.R. (2011a). Depth-averaged drag coefficient for modeling flow through suspended canopies. *Journal of Hydraulic Engineering 137*: 234–247.

Plew, D.R. (2011b). Shellfish farm-induced changes to tidal circulation in an embayment, and implications for seston depletion. *Aquaculture Environment Interactions 1*: 201–214.

Plew, D.R.; Spigel, R.H.; Stevens, C.L.; Nokes, R.I.; Davidson, M.J. (2006). Stratified flow interactions with a suspended canopy. *Environmental Fluid Mechanics 6*: 519–539.

Plew, D.R.; Stevens, C.L.; Spigel, R.H.; Hartstein, N.D. (2005). Hydrodynamic implications of large offshore mussel farms. *IEEE Journal of Oceanic Engineering 30*: 95–108.

Seymour, R.J.; Hanes, D.M. (1979). Performance analysis of tethered float breakwaters. *Journal of Waterway, Port, Coastal and Ocean Engineering 105*: 265–280.

Shi, J.; Wei, H.; Zhao, L.; Yuan, Y.; Fang, J.; Zhang, J. (2011). A physical-biological coupled aquaculture model for a suspended aquaculture area of China. *Aquaculture 318*: 412–424.

Slater, M.J.; Carton, A.G. (2007). Survivorship and growth of the sea cucumber *Australostichopus (Stichopus) mollis* (Hutton 1872) in polyculture trials with green-lipped mussel farms. *Aquaculture 272*: 389–398.

Smith, K.A.; North, E.W.; Shi, F.; Chen, S.N.; Hood, R.; Koch, E.; Newell, R. (2009). Modeling the effects of oyster reefs and breakwaters on seagrass growth. *Estuaries and Coasts 32*: 748–757.

Smith, R.; McDonald, P.S. (2009). Examining the effects of predator exclusion structures associated with geoduck aquaculture on mobile benthic macrofauna in south Puget Sound, Washington. *Journal of Shellfish Research 28*: 730–730.

van Duren, L.A.; Herman, P.M.J; Sandee, A.J.J.; Heip, C.H.R. (2006). Effects of mussel filtering activity on boundary layer structure. *Journal of Sea Research 55*: 3–14.

Venayagamoorthy, S.K.; Ku, H.; Fringer, O.B.; Chiu, A.; Naylor, R.L.; Koseff, J.R. (2011). Numerical modeling of aquaculture dissolved waste transport in a coastal embayment. *Environmental Fluid Mechanics 11*: 329–352.

Williams, A.N.; McDougal, W.G. (1996). A dynamic submerged breakwater. *Journal of Waterway, Port, Coastal and Ocean Engineering 112*: 288–296.

Yu, X. (1995). Diffraction of water waves by porous breakwaters. *Journal of Waterway, Port, Coastal and Ocean Engineering 121*: 275–282.