The interference of hydro-electric power production with natural effects of the North Atlantic hydrological cycle on a marine food web

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THE INTERFERENCE OF HYDRO-ELECTRIC POWER PRODUCTION WITH NATURAL EFFECTS OF THE NORTH ATLANTIC HYDROLOGICAL CYCLE ON A MARINE FOOD WEB

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Key words: Hydro-electric, North Atlantic, Hydrological cycle, Marine food web, cod, copepod

Abstract
During positive phases of the North Atlantic Oscillation (NAO) westerly winds carry Atlantic water vapor to high latitudes and causes large precipitation in Scandinavia. The melting of winter precipitation determines the freshwater discharge to Norwegian coastal waters in May-July. The discharge and two population variables from the NE Arctic cod (*Gadus morhua*) stock have been positively correlated with 1 and 3 year lags, respectively. Thecorrelations may be explained by the ecological key role of the copepod *Calanus finmarchicus*. Its nauplii (juveniles) is the first prey for larvae of NE Arctic cod when they start feeding in northern Norwegian shelf waters in April-May. The abundance of nauplii is proportional to the parent stock that possibly originates from reproduction in the Norwegian Coastal Current (NCC) during the previous summer, in the period of maximum river discharge. When the parent generation accumulates in fjordic wintering habitats prior to their reproduction in the following spring, their abundance is positively correlated with NAO averaged over the previous spring and summer, when it forces ecological processes in their juvenile habitat. However, the anthropogenic regulation of river flow by hydroelectric power production in Norway impairs the effects of the natural hydrological cycle, by reservoirs that store meltwater and release the water at other seasons. The generating of electricity has decreased the summer discharge of meltwater by more than 50 % in some coastal regions. The cumulative effects of numerous hydroelectric plants along the coast have possibly changed the biological productivity and fish stock recruitment in Norwegian waters, but at present the extent can not be assessed. Similar concerns has been expressed in Canadian scientific journals, and the problem may be valid in European shelf waters that receive regulated river flow.

Mots clés : *hydroélectricité, Atlantique nord, cycle hydrologique, chaîne alimentaire marine, morue, copépode*

Résumé : *Pendant les phases positives de l'Oscillation Nord Atlantique (ONA), des vents d'ouest transportent les masses de vapeur d'eau Atlantique vers les hautes latitudes, induisant de fortes precipitation en Scandinavie. La fonte des précipitations hivernales contrôle la décharge d'eau douce dans les eaux cotières norvégiennes en Mai – Juillet. La décharge et deux variables populationnnelles pour les stocks de morue NE Arctique* (Gadus morua) *ont été corrélées positivement avec 1 et 3 ans d'intervalle, respectivement. Les corrélations peuvent etre expliquées par le role écologique clé du copépode* Calanus finmarchicus. *Ses nauplii (juvéniles) sont les proies privilégiées pour les larves de morues NE Arctique quand elles commencent à se nourrir dans les eaux du plateau continental au nord de la Norvège en Avril – Mai.*
L'abondance des nauplii est proportionnelle au stock parental qui vient de la reproduction dans le Courant Cotier Norvégien (CCN) durant l'été précédent, dans la période de décharge fluviale maximum. Quand la génération parentale s'accumule dans les habitats hivernaux de fjords avant la reproduction qui a lieu au printemps suivant, leur abondance est corrélée positivement avec l'ONA moyennée sur le printemps précédent et l'été quand cela induit des processus écologiques dans leur habitat juvénile. Toutefois, la régulation anthropique du flux de la rivière par la production hydroélectrique en Norvège découple les effets du cycle hydrologique grace aux réservoirs qui stockent l'eau de fonte des neiges et relarguent les eaux à d'autres saisons. La production d'électricité a diminué le relarguage estival d'eau de fonte par plus de 50% dans certaines régions cotières. Les effets cumulés des nombreuses stations hydroélectriques le long de la cote ont certainement changé la productivité biologique et le recrutement des stocks de poissons dans les eaux norvégiennes mais dans une proportion qui n'a pas été encore évaluée présentement. Des craintes similaires ont été exprimées par des journaux scientifiques canadiens et le problème peut également etre valide dans les eaux du plateau continental européen qui reçoivent les cours fluviaux régulés.

INTRODUCTION

At latitudes of about 30^{o} N, dry air sinks from the upper troposphere to the sea surface in the North Atlantic. It generates a high pressure region that is the source of air masses transported near the sea surface towards Europe by westerly winds. During the transportation, radiation of solar energy to the ocean causes loading of water vapour into the air masses. The intensity of the wind field and the tracks of westerly storms towards Europe depends on the latitudinal atmospheric pressure gardient between the high pressure region and the low pressure trough at about 60^{o} N. Hurrell (1995) referred to these pressure differences as the North Atlantic Oscillation (NAO), calculated from measurements at the Azores and Iceland.

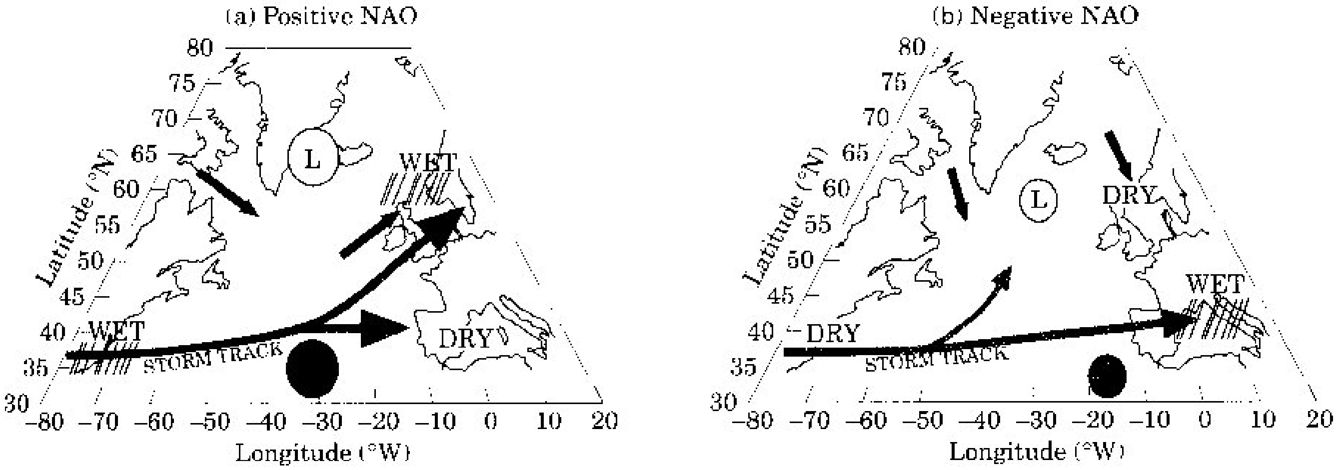

Figure 1. Atmospheric conditons over the North Atlantic associated with a) positive and b) negative phases of the NAO (From Greene and Pershing 2000).

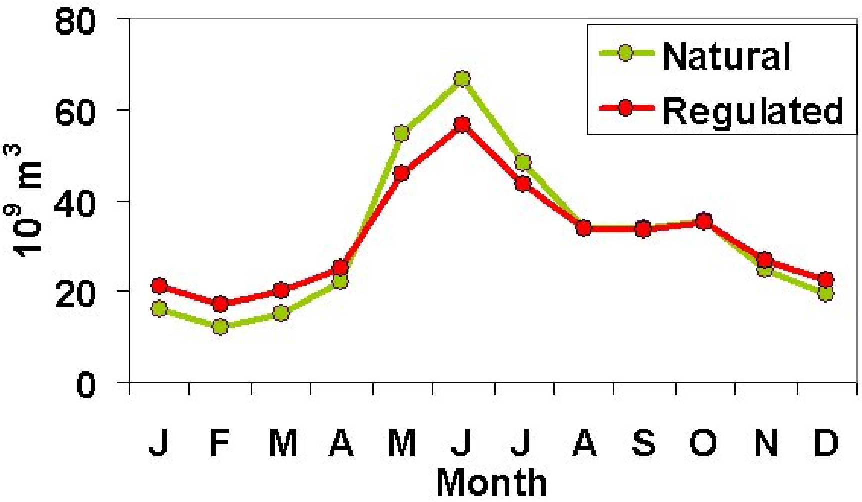

Figure 2 : Natural runoff (green) from Norwegian precipitation areas, and discharge to the sea (red) influenced by regulation for production of hydro-electric energy (Data from 1963-1972 presented by Asvall 1976).

During periods of negative NAO (below average), the storm tracks hit southern Europe and causes a wet climate there, while in Scandinavia northerly winds causes a dry climate (Fig. 1). When NAO is positive (above average), the westerly winds intensify and the storms follow tracks towards Scandinavia where a mountain range lifts the oceanic air flow. The resulting adiabatic cooling forces precipitation that during winter in high altitudes is mostly accumulated as snow. It is stored untill the meltwater discharge season in May-July. Today, much of the meltwater from Norwegian territory is not discharged into the sea during summer, but delayed by storage in dams built for production of hydro-electric energy. As early as in 1969-73, the discharge in July was on a national average reduced by 16% (Fig. 2), and up to more than 25% on regional scales (Asvall 1976). Since then, several large water-courses have been developed for hydro-elecric production, but the total effect on seasonal discharge to the sea is not known.
Several scientists have suggested that seasonal freshwater discharge to the NE Atlantic stimulated the biological productivity in Norwegian coastal waters (Helland-Hansen and Nansen 1909, Gran 1923, Izhevskii 1964, Skreslet 1976). Skreslet (1981) expressed concern that freshwater regulation would potentially affect the production of fisheries resources. The present account rephrases this concern, based on more recent empirical evidence.

RESPONSES OF AN ECOSYSTEM TO CHANGING NAO

The Arctic Mediterranean (Tchernia 1980) is enclosed by the North American and Eurasian continents and may be defined as one large ecosystem (Skreslet 1997). It contains populations of arctic and boreal species that in biogeographical respects overlap within the Sub-Arctic Transitional Zone (Fig. 3). Particular species are more or less endemic to the transitional zone, like *Calanus finmarchicus*, a herbivorous copepod that populates the northern north Atlantic, from the east coast of USA to the Atlantic coast of Russia. Bucklin *et al.* (2000) observed only small-scale genetic heterogeneity in specimens from one of its population systems that is established in the Nordic

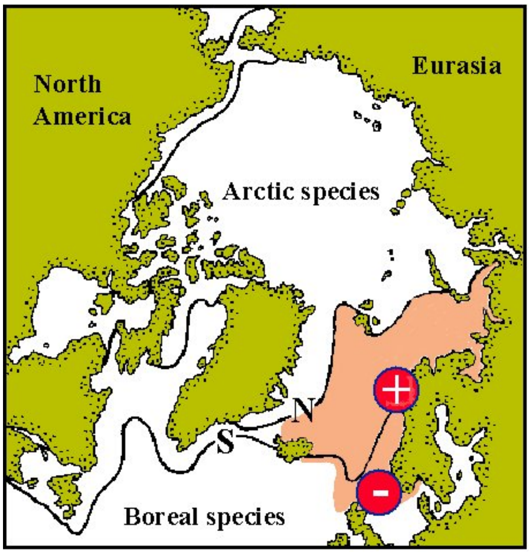

Figure 3: The Arctic Mediterranean with the sub-arctic transitional zone situated between the southern limit of arctic species (S) and the northern limit of boreal species (N), according to Ekman (1967). The geographical distribution of the *C. finmarchicus* population system of the Nordic and Barents Seas is drawn in pink. Red dots indicates regions where the abundance of *C. finmarchicus* has been observed to be negatively (Fromentin and Planque 1996) and positively (Skreslet and Borja, in press) correlated with NAO, respectively.

and Barents Seas. The population plays an ecological key role as a major trophodynamic link between planktonic primary production and higher trophic levels in the food-web. It is an important food source in the entire life cycle of planktivores like herring (*Clupea harengus*) and capelin (*Mallotus villosus*), and as juvenile food for fish being piscivores and feeders on benthos in their adolescent and adult life stages.

The abundance of *C. finmarchicus* fluctuates with the NAO (Fig. 3). A negative correlation is observed in the North Sea (Fromentin and Planque 1996), while a positive correlation emerges in material from northern Norway (Skreslet and Borja, in press). The discrepancy may be explained by the shift from westerly winds in periods of positive NAO to northerly winds during negative NAO (Fig. 1). Changing wind stress over the Norwegian Sea may cause the inflow of Atlantic water to vary accordingly, displacing parts of the population to the northwards in years when positive NAO predominates, and *vice versa*. However, the adverse effects of NAO on *C. finmarchicus* in the two regions may also result from its hydrological dimensions.

The increased precipitation that probably results from positive NAO (Fig. 1) during late winter and spring probably increases the vernal freshwater outflow to Norwegian coastal waters during summer. It may influence the stratigraphy of the eastern Norwegian Sea, as well as the mixing in oceanographical fronts and advection by currents. The inner mid-Norwegian shelf is a summer spawning habitat for *C. finmarchicus* (Skreslet and Olsen, submitted) that may originate as a first generation from spring spawning habitats in the North Sea region (Heath *et al.* 1999). The abundance of their nauplii in the frontal region of the Norwegian Coastal Current (NCC) was observed to be negatively correlated with salinity (Fig. 4), suggesting that the production of a new generation may be proportional with the seasonal freshwater discharge.

While the positive correlation between NAO in March-July and abundance of *C. finmarchicus* in northern Norway (Skreslet and Borja, in press) may be explained by increased biological productivity, the negative correlation in the Noth Sea (Fromentin and Planque 1996) may not. Considering years with positive NAO, increased freshwater outflow from Norway and Russia to the Arctic Mediterranean Ecosystem possibly causes increased stratification and decreased formation of deep-water in the Greenlad Sea. Heath *et al.* (1999, 2000a) assume that *C. finmarchicus* spending the winter in diapause at more than 600 m depth may be advected southwards in the Norwegian Sea, towards the North Sea shelf. Thus, in periods of years with negative NAO, Greenland Sea deep-water formation would be large and increase the southward return flow of recruit spawners to the North Sea. That would support a more southward displacement of the population.

EFFECTS OF FRESHWATER OUTFLOW ON PRODUCTION OF FISH.

Skreslet (1976) observed that the survival of 0-group North-East Arctic cod (*Gadus morhua*) was positively correlated with Norwegian vernal freshwater outflow in 1946-1960. The best correlation ocurred with discharge to the south of the Mid-Norwegian shelf in the previous year. On a later occasion this correlation was observed to break down when the time series was prolonged. However, before the period of break-down, landings of juvenile cod caught in the southern Barents Sea became positively correlated with vernal discharge three years in advance (Fig. 5).

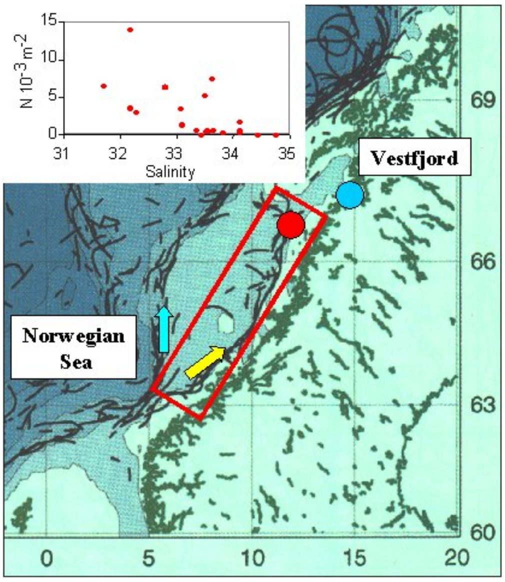

Figure 4. Supposed summer reproduction habitat of *C. finmarchicus* (red rectangle) on the inner mid-Norwegian shelf. Inserted scatter plot (from Skreslet and Olsen, submitted) shows relationship between surface salinity and abundance of *C. finmarchicus* nauplius stage I+II.investigated in 1997 (under red dot). Black drifter trajectories indicate current velocities > 40 cm s^{-1} (from Poulin *et al.* 1996). Arrows indicate the direction of the Norwegian Coastal Current (yellow) and the shelf break current (blue). Blue dot: Sampling locations for observed positive correlation (Skreslet and Borja, in press) between NAO and abundance of wintering *C. finmarchicus*.

A synoptic assessment of empirical information (Skreslet 1997) lead to a conceptual model that explains the possible causal relationships that link populaton variables in NE Arctic cod to freshwater discharge (Fig. 6). The model assumes that a population of *C. finmarchicus* transfer the hydrological signal of NAO from Norwegian freshwater discharge volumes to higher levels in the ecosystem. It couples the *C. finmarchicus* population ecology to freshwater outflow when CV of the first North Sea generation is brought onto the mid-Norwegian shelf by the NCC. Their offspring that results from reproduction in the NCC frontal zone during summer (Skreslet and Olsen, submitted) is supposedly identical to the wintering generation that accumulates as adolescent copepodites in stage CV in the wintering habitats of the Vestfjord region (Heath *et al.* 2000b, Skreslet *et al.* 2000), in numbers being positively correlated with NAO (Skreslet and Borja, in press).

Next spring the wintering generation of *C. finmarchicus* spawns in concert with NE Arctic cod (Ellertsen *et al.* 1984). The cod yearclass strength may to some extent depend on the spawning stock biomass (i.e. number of eggs spawned). However, juvenile *C. finmarchicus* in naupliar stages NI-VI is the food source that determines the survival rate of cod larvae and one of the forcing factors is the abundance of reproducing females. After metamorphosis, the year-class strength is established in the stock of 0 group cod (fry of the year) that drift by the NCC into the southern Barents Sea. This chain of interrelated factors is suggested to explain the positive correlation between freshwater outflow and cod larval survival with a lag of one year (Fig. 5).

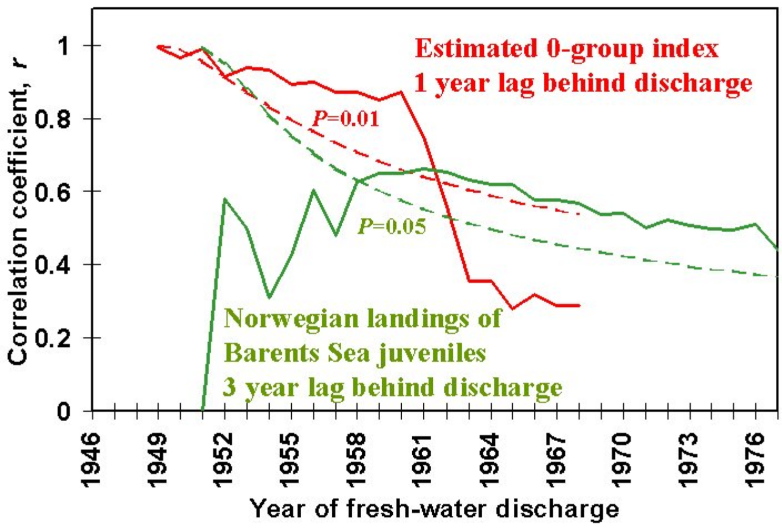

Figure 5 : Stepwise correlation with population variables from the NE Arcic cod stock as functions of freshwater discharge to the south of tyhe mid-Norwegian shelf (Redrawn after Skreslet 198x). Stipled curves: Critical value.

The model assumes that 0-group cod compete for prey with I-III group cod after they have entered the Barents Sea, and it takes into account that juvenile cod are cannibalistic. Years with high NAO may therefore not only result in one strong, fast-growing 0-group year-class, but also increase the growth rate in older year-classes. That would cause cod from several year-classes to recruit to the fisheries simultaneously, ranging from large two-year old to small five-year old fish. This is how the model explains the lag of three years in the positive correlation between freshwater outflow and landed catches of juvenile cod from the southern Barents Sea (Fig. 5).

EFFECTS OF FRESH-WATER REGULATION

The effects of river runoff as a land-ocean interaction has mostly been associated with water as a medium that carry substances of natural and anthropogenic origin. Little emphasis has been put on the anthropogenic regulation of the flow of water itself, as volumes of mass. Apart from being a discussion in Norway (Skreslet 1981, 1986, Kaartvedt 1984), only the Canadian scientific community has addressed the problem. Neu (1976, 1982ab) raised the question after Sutcliffe (1972, 1973) observed that commercial catches from the Gulf of St. Lawrence was positively correlated with river flow. However, a public Canadian committee (Bugden *et al.* 1982) concluded that there is conflicting evidence that regulation of river flow would reduce the production of marine resourses. Two international meetings raised the same problem and stated that lack of knowledge prevented the establishment of conclusive evidence (Skreslet *et al.* 1976, Skreslet 1986).

The complex relationships involved call for ecological modelling that nests a number of numerical models from different fields of science. There are promising models that simulate the production of *C. finmarchicus* as a function of physical forcing factors and phytoplankton production but the hydrological input data are insufficient. Norway has still no hydrological model that calculates the seasonal and interannual variation in freshwater outflow to the sea, taking into account the sum of unregulated and regulated discharge.

The lack of scientific cooperation between planktologists and fisheries biologists also poses a problem. Fisheries management of exploited stocks has had priority over the development of numerical fish population studies that could focus on effects of environmental forcing variables. At present, the nesting of fish population models with plankton production models is not easily attained, although there are obvious reasons to do so.

Most European water courses have been regulated for domestic and industrial purposes, having obviously altered the oceanography of neritic resipients, with unanticipated and unknown consequences for populations of marine organisms. The problem calls for ecological cooperation between hydrologists, limnologists and oceanographers from different disciplines of science.

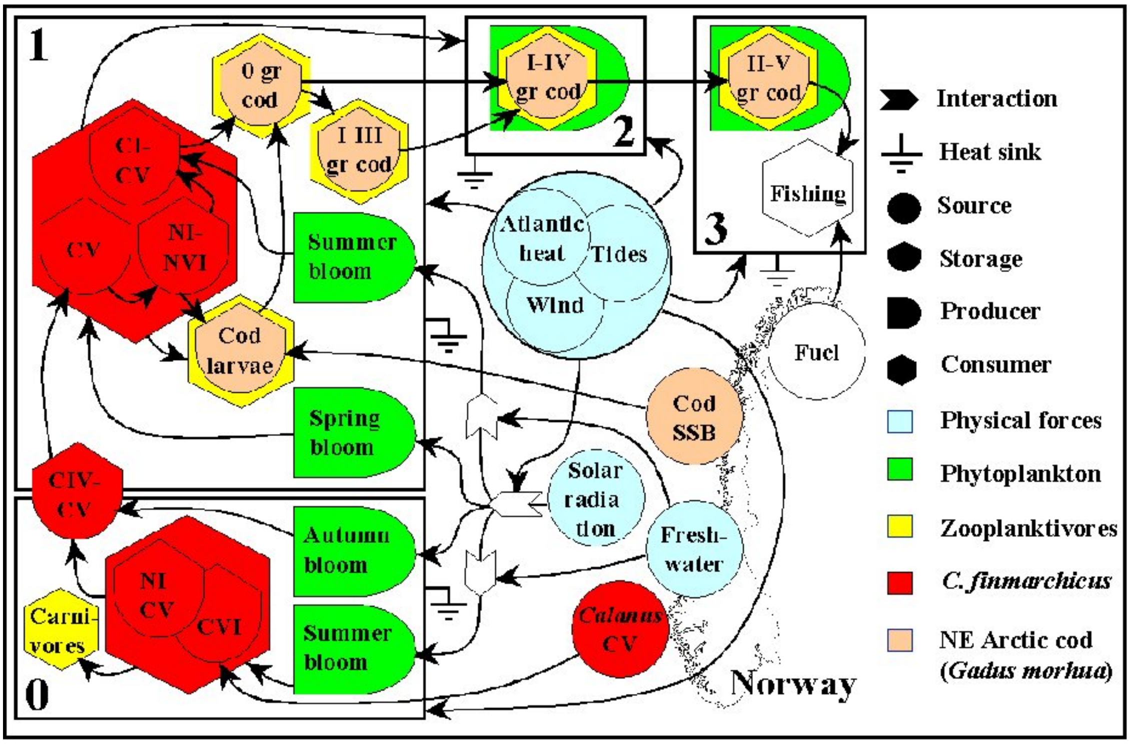

Figure 6 : Conceptual model of energy flow in time and space along the Noregian coast (modified from Skreslet 1997). The initial processes (year 0) occur on the mid-Norwegian shelf. Processes in the following year occur from Lofoten to the southwestern Barents Sea, while processes in the two last years (year 2 and 3) occur in the southeastern Barents Sea. Ikons are according to Odum (1971). NI-CVI are moulting stages of *C. finmarchicus*. SSB: Spawning stock biomass. 0-V gr cod refer to age groups.

CONCLUSION

There is a serious lack of understanding of the marine ecological role of rivers, and how the anthropogenic regulation of freshwater flow affects processes on the basin-scale level of ecosystems. Important reproduction habitats of *C. finmarchicus* are influenced by freshwater discharge. Taking into account the key role of its populations in the northern North Atlantic, regulation of river flow may be expected to influence the production of marine fish. Scientific solving of this problem will require the involvement of traditionally separated fields of science, and nesting of large numerical models.

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