Potential for Impairment of Freshwater Mussel Populations in DRBC Special Protection Waters as a Consequence of Natural Gas Exploratory Well Development

By

Robert M. Anderson, Fish & Wildlife Biologist, U.S. Fish & Wildlife Service
Expert in Freshwater Mussels and Mussel Habitat

and

Danielle A. Kreeger, Ph.D., Science Director,
Partnership for the Delaware Estuary
Expert in Aquatic Ecology and Functional Ecology

November 23, 2010

Our testimony addresses the question of whether natural gas exploratory wells have the potential for a substantial effect on the quality of waters classified by the Delaware River Basin Commission (DRBC or "Commission") as Special Protection Waters (SPW), for which the Commission has established a policy of "no measurable change except towards natural conditions . . . ." *DRBC Water Quality Regulations* § 3.10.3 A.2. We focus on the water quality value and susceptibility to impairment of freshwater mussel populations, which both depend upon and contribute to the exceptional water quality of the main stem upper and middle Delaware River. We also highlight characteristics of the dwarf wedgemussel, a federally listed endangered species found in portions of the main stem upper Delaware River and its tributaries underlain by the Marcellus shale. The dwarf wedgemussel is particularly susceptible to siltation, hydrologic changes, exposure to contaminants, and losses of population caused by invasive species, all of which are likely to accompany the development of natural gas in the region, including the construction of exploratory wells. We contend that in light of the potential for adverse effects on water quality and aquatic resources as a result of natural gas exploratory well development, regulation by the Delaware River Basin Commission is warranted. Such regulation may help to prevent impairment, ensure that any water resource impacts, should they occur, are measured, and require that those responsible for causing damage to water quality and aquatic resources have the means and legal obligation to perform restoration.

I. Freshwater Mussel Status and Trends in the Delaware Basin

Freshwater mussels include abundant species that are vital for ecosystem function. These are also the most imperiled of all animals and plants in the Delaware River Basin, as elsewhere in North America (Williams et al. 1993.) This otherwise highly successful and diverse group has specific life history characteristics that contribute to their apparent sensitivity and have resulted in substantial declines in range and abundance of some species. These characteristics include a dependence upon populations of an unrelated species of fish for successful reproduction, low annual recruitment balanced by a long reproductive life-span, relative immobility, and filtering of water to extract food.

II. Mussel Assemblages in the Delaware River System

Population Abundance and Biodiversity

As a result of being undammed and well managed, the upper mainstem Delaware River retains healthy numbers of several native species of freshwater mussels (Lellis 2001, Lellis 2002). Although there are numerous state and federal listed imperiled species in the basin (e.g. dwarf wedgemussels), the numerical health of the collective mussel assemblage is sizeable in the river itself, extending down even into the tidal areas of the Delaware River.

Approximately 60 species of bivalve mollusks live in headwater streams and lakes of the Delaware basin as well as in the non-tidal main stem and other large tributaries, freshwater tidal areas, and in the brackish and saline portions of the Estuary (Kreeger and Kraeuter 2010).

Approximately 12-14 species are native freshwater mussels (Unionidae, Table 1) based on historical accounts (e.g., Ortmann 1919.) Numerous species of special concern to PA and NJ are known to remain in portions of the basin (Table 1) including the Upper Delaware. Although the status terminology varies among states, nine of the twelve remaining native species are deemed imperiled by New York, New Jersey, Pennsylvania, and/or the Federal Government, or are deemed to be globally imperiled (Table 1.)

Scientific Name	**Common Name**	**Conservation Status**			
		NY Status	**NJ Status**	**PA Status**	**Global/ Federal Status**
Alasmidonta heterodon	Dwarf wedgemussel	Critically imperiled/ **Endangered**	Critically imperiled/ **Endangered**	Critically imperiled/ **Endangered**	Critically imperiled/ **Endangered**
Alasmidonta undulata	Triangle floater	Apparently secure	Imperiled/ **Threatened**	Vulnerable	Apparently secure
Alasmidonta varicosa	Brook floater	Critically imperiled/ **Threatened**	Critically imperiled/ **Endangered**	Imperiled	Vulnerable/ **Species of concern**
Anodonta implicata	Alewife floater	Critically imperiled	Secure	Not ranked	Secure
Elliptio complanata	Eastern Elliptio	Secure	Secure	Secure	Secure
Lampsilis cariosa	Yellow lampmussel	Vulnerable	Imperiled/ **Threatened**	Vulnerable	Vulnerable
Lampsilis radiata	Eastern lampmussel	Apparently secure	Imperiled/ **Threatened**	Critically imperiled	Secure
Leptodea ochracea	Tidewater mucket	Critically imperiled	Imperiled/ **Threatened**	Critically imperiled/ extirpated	Vulnerable
Ligumia nasuta	Eastern pondmussel	Vulnerable	Critically imperiled/ **Threatened**	Critically imperiled	Apparently secure
Maragatifera maragatifera	Eastern pearlshell	Imperiled	Not ranked Proposed	Critically imperiled/ **Endangered**	Apparently secure

			Endangered		
Pyganodon cataracta	Eastern floater	Apparently secure	Secure	Vulnerable	Secure
Strophitus undulatus	Creeper	Apparently secure	Vulnerable/ **Species of concern**	Apparently secure	Secure

Table 1. Conservation status of native freshwater mussel species of the Delaware River watershed. Bold text indicates legally protected species status by state. Natural Heritage status accessed on NatureServe (www.natureserve.org) on November 16, 2010.

Within the Delaware basin, colonies of dwarf wedgemussels, a federally listed endangered species, currently are found only in portions of the main stem upper Delaware River and in four tributaries – the Neversink River, within the drainage area of DRBC Special Protection Waters in New York State, and the Flat Brook/Little Flat Brook, Paulins Kill River and Pequest River in New Jersey. The distribution of dwarf wedgemussels was once much wider across the mid-Atlantic watersheds than it is today.

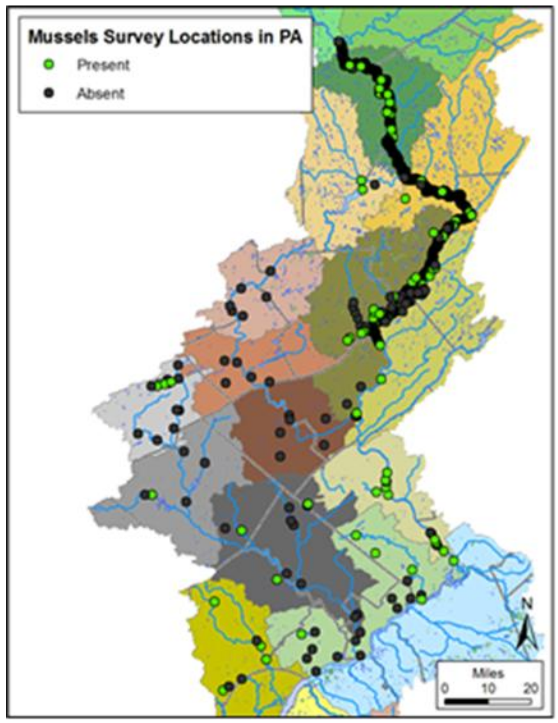

Figure 1. Presence and absence of freshwater mussels in Pennsylvania locations where they were historically reported as surveyed by various researchers since 1980.

The natural mixed-species assemblage of mussels would have consisted of aggregated populations of numerous species, occupying different niches (benthic habitats) within the stream, and collectively filtering a tremendous amount of water. Today, only one of our native 12+ mussel species can be readily found (*Elliptio complanata*). Unfortunately, mussel abundance appears greatly reduced in virtually all tributary streams and rivers in the Delaware River Basin. (PDE 2008.)

Based on the limited current distribution of mussels of any species in tributary streams (<10% in southeast PA, limited surveys elsewhere, Fig. 1), and the patchiness and low mussel abundance (<1 m^2) within streams where they are found (often only in wooded reaches), the healthy assemblages that exist in the main stem and tributaries of the Upper Delaware are particularly valuable and require protection.

Preservation of Existing Colonies is Critical to Stemming Mussel Declines

A number of factors make it critically important that existing colonies be preserved to serve as broodstock for restoring populations to streams from which they have been lost.

Mussels likely become extirpated from streams because of either: 1) general impaired water or habitat quality, 2) specific incidents (i.e. spills) that cause acute mortality in a single event, 3) overharvesting/predation, or 4) loss of fish host species to support larval growth and distribution.

Once extirpated from a stream or reach, mussels are not able to recolonize easily, particularly if there is no longer broodstock nearby. In some tributaries, dams and other impediments to fish passage may block dispersal of juveniles (via fish hosts, see life history below) back into the stream (McMahon 1991). Most mussels have a long lifespan (30-100 years) and don't reproduce until at least 8 years old. Therefore, even if conditions permit redistribution via fish hosts, recolonization and recovery can take decades.

Remaining mussel beds in the Delaware River are vulnerable to spills and land-based development. Protection of the existing metapopulation includes ensuring that it does not become further fragmented, less able to disperse and exchange genes, and as a result, less resilient.

III. Importance of Freshwater Mussels

There are societal and ecological reasons for maintaining large populations of filter feeders in aquatic ecosystems. Where abundant, they help to maintain water quality, stabilize substrates, decrease erosion, and create beneficial habitat complexity. Some species are also commercially and historically important. Filter-feeders are effective at accumulating many classes of contaminants and so are useful in assessing water and sediment contamination in specific areas and for specific time periods. The health of individual bivalves and assemblages of bivalves can directly indicate the health of the aquatic ecosystem.

Ecosystem Function Values

Freshwater mussels, like most bivalves, are considered "ecosystem engineers" because they modify habitat complexity and improve water quality, often dominating the ecology of rivers and streams where they are still abundant. Similar to oyster and coral reefs, these animals form dense assemblages that create habitat conditions beneficial for other organisms. The habitat benefits are myriad, including physical, chemical, and biological modifications. They help to stabilize stream channels and decrease bed transport during high flow events (physical). The vertical structure of large-bodied mussels also furnishes stable microhabitats for benthic macroinvertebrates and fish (physical). Mussel shells protruding from the bottom increase turbulent mixing in the benthic boundary layer and provide refugia for other fauna.

Through their biodeposits (agglutinated mussel feces and pseudofeces), mussels enrich sediments (Vanni 2002, Howard and Cuffey 2005) with organic materials and biochemical compounds (chemical) providing for enhanced benthic algal production and greater food resources for other benthic fauna (biological).

Although mussel beds provide many ecosystem services such as streambed stabilization and enrichment of sediments for other animals and plants, they are most valued for their water processing ability. Mussels improve water quality by removing suspended particulates through filter-feeding. Each adult mussel filters liters of water per day during the growing season, and the combined biofiltration by beds of mussels in healthy streams may exceed the system's downstream flushing volume. For instance, Dr. Kreeger estimated that a relic population of 500,000 mussels on the lower Brandywine River in Pennsylvania still filters more than 1 billion liters and removes 26 metric tons of dry total suspended solids (TSS) each summer season. This population is old, may not be reproducing, and represents a fraction of the system's carrying capacity for mussels. Approximately 4 billion *E. complanata* are estimated to reside in the Delaware River Basin today and they collectively filter about 10 billion liters of water per hour in the summer (Kreeger, unpublished).

Water quality and mussel abundance in the main stem and tributaries affect the ecosystem health of the Delaware Estuary. Kreeger and Kraeuter (2010) estimated that populations of all bivalve species in the Delaware Estuary watershed collectively filter more than 100 billion liters of water every hour during warmer seasons (10^8 m^3 hr^{-1}). If true, this represents about 2500 times the volume of freshwater entering the tidal estuary every hour (Kreeger and Kraeuter 2010.) Still, many streams contain no mussels at all, and others, such as the lower Brandywine, host older populations that may not be reproducing.

Biofiltration by mussels has direct implications for reduction of impacts of stormwater runoff and particulate nutrient control. Since much of the material filtered from the water column (e.g. particle bound nutrients, phytoplankton) is metabolized and then either used by the mussels or transformed into usable materials by other organisms, mussels facilitate nutrient control in streams and rivers.

Other important ecosystem functions include serving as prey for wildlife, biogeochemical cycling and remineralization, and in some areas facilitation of microbial denitrification. Freshwater mussels are eaten by many mammals and birds (van Tets 1994, Tyrrell and Hornbach 1998). Mussels therefore represent important links in aquatic food webs by feeding on microscopic matter at the base of the food chain and in turn being eaten by secondary consumers such as vertebrates.

In healthy rivers such as the main stem upper Delaware River where mussels are numerous, base-of–food-web conditions are richer and ecological turnover rates higher, compared to streams with few mussels.

In summary, healthy beds of mussels provide a multitude of structural and functional services including nutrient sequestration and cycling, substrate stabilization, suspended sediment removal, and the transfer of particulate matter from the water column and into easily assimilated foods for other aquatic species, including fish (Bauer and Wächtler 2001, Pusch et al. 2001, Kreeger 2004).

<u>Bioindicator Value</u>

Mussels are long-lived "sentinel bioindicators", meaning their abundance, biodiversity, and physiological health can tell us a great deal about overall environmental conditions (Kreeger et al. 2002; Martel et al. 2003, PDE 2008). Being relatively sessile, long-lived (up to 100 years), and sensitive to environmental conditions, freshwater mussels are excellent bioindicators of long-term changes in watershed condition. Due to their limited mobility that prohibits their movement to escape suboptimal environmental conditions, mussel fitness and population vigor is therefore directly indicative of local conditions. In addition, they are indicators of long-term habitat stability because their riverbed habitat is dependent on channel hydraulics and sediment transport.

Internationally, suspension-feeding bivalves have long been considered to be among the best bioindicators of aquatic ecosystems (Dame 1996). For example, in 1976 the U.S. instituted the "Mussel Watch Monitoring Program" to examine the environmental impact of pollution in aquatic ecosystems. Although initially conceived as including bivalves in marine, estuarine and freshwater habitats, the concept was embraced primarily by scientists and resource managers in marine habitats, and the program thereafter focused on marine species such as oysters and blue mussels. The program has been extended to the United Kingdom, France, Canada, Australia, Japan, Taiwan, India, South Africa and the Soviet Republic. In 1986, the U.S. program evolved into the National Status and Trends Mussel Watch Project. Today, a diverse array of chemical and biological contaminants is uniformly analyzed in bivalve tissue from more than 280 coastal sites in the U.S. Mussel Watch.

A comparable, bivalve-based biological monitoring program for freshwater systems is technically feasible but not yet developed, although many studies are now using caged mussels to monitor water quality (e.g., Kreeger et al. 2002).

Due to their unparalleled ability to filter water and improve water quality, suspension-feeding bivalves such as mussels are also perceived as top restoration targets, because enhanced mussel populations will promote positive feedbacks for water and habitat quality, which then benefit mussels. Again, where we are fortunate to have healthy mussel colonies, it is essential that they be preserved.

IV. Potential for Impairment of Freshwater Mussels as a Result of Activities Associated with Development of Natural Gas Exploratory Wells

The greatest diversity and abundance of mussels are associated with clean-swept sand and gravel substrates, but as largely sessile organisms, the complex life history traits of mussels make it possible for populations to thrive in a highly dynamic environment where rapid changes in flow and water quality can occur at each rain event. These same adaptations, however, limit the ability of freshwater mussels to withstand, or recover from, lethal and chronic impacts to which these animals are sensitive, such as increased siltation, water quality alteration, hydrologic alteration, and introduced species. These factors are discussed in greater detail below.

Sedimentation

Mortality, injury and stress to mussels from siltation and other types of sedimentation caused by onshore construction (*i.e.*, staging areas and access road use) is more likely to occur near the source, but erosion and siltation in tributaries at distant locations in the watershed can cause damage when this material is flushed downstream. Silt in the form of increased turbidity and suspended sediment transport is detrimental to mussel health and habitat because it reduces the depth of light penetration leading to alteration of primary productivity, decreases oxygen levels, increases water temperature, irritates or clogs mussel gills, and deposits silt on the substrate.

High turbidity may also interfere with sight lures, such as conglutinates, which attract host fish. Silt that settles from the water column can smother, bury and/or clog the gills of freshwater mussels unable to avoid these effects due to the extent of siltation or particular phase of the animals' annual life history (for example, gravid female mussels hold eggs and young within a specialized gill structure for weeks to months of a year).

Silt deposition also affects mussels by smothering the eggs or larvae of the fish host populations and by reducing food availability for either the fish or the mussels themselves. Siltation also may result in reduced dissolved oxygen and increased organic material at the substrate level (Ellis 1936, Harman 1974) even when it does not blanket the substrate due to quantity or local water velocity. Silt that settles between sand and gravel particles alters water flow, food and oxygen through the gravel. The interstitial space between sand and gravel is vital for spawning habitat and survival of young host fish and juvenile mussels. When this area becomes unsuitable for juvenile mussels, the population may be unable to reproduction even when the adults continue to survive. Finally, alteration of sediment grain size or excessive volumes of highly mobile soft sediments can increase the risk of scour and hinder the sediment-stabilization benefits of mussels

Excessive sedimentation reduces suitable bottom habitat for mussels, leading to reduced populations and reduced ecosystem services.

Excessive sedimentation can smother mussels, causing acute mortality, reduced populations and reduced ecosystem services.

Suspended Sediments

As filter feeders on microscopic food items, mussels are very susceptible to not only acute mortality due to smothering by silt but also high sediment loads in the water. High turbidity can directly hinder or prevent filter-feeding and respiration when mussels close their valves to avoid intake of silt. At sublethal levels, silt interferes with feeding and metabolism in general (Aldrige *et al*. 1987) because the mussels must divert more energy to sort silt particles from food, again resulting in starvation. Over time, this will reduce an animal's fitness through starvation and, at the population scale, decreases biofiltration services.

Finally, chemicals and compounds are often bound to, and mixed with, fine silts due to their high surface area-to -volume ratio and positive charge. While mussels have some ability to select particular particle sizes, they indiscriminately feed on vast numbers of these small particles, both organic and inorganic. Since particle capture is achieved on the soft tissue gills, which are also used for gas exchange (countercurrent), they have a high degree of exposure to any particle-associated chemicals. Furthermore, particle sorting is inefficient on the gills and labial palps prior to ingestion, so these animals unavoidably consume a variety of non-food particles. Although the chemical conditions in the digestive tract of the mussel can metabolize or mobilize some of the particle-associated contaminants, the high surface area-to -volume ratio of the very small particles exposes the animal to higher levels of toxic compounds than non-filter feeding species that consume larger prey.

In summary, filter feeding bivalves such as freshwater mussels are typically exposed to greater amounts of both waterborne dissolved contaminants and particle-associated contaminants than other aquatic organisms. Although some classes of contaminants can be broken down through metabolism, most tend to be bioaccumulated within the tissues of the animals, leading to either acute mortality, chronic stress, or mediation into the food web as other animals prey on mussels. For these reasons, bivalves are regarded as sentinel bioindicators around the world; e.g. by International Mussel Watch.

Excessive suspended sediments can impair feeding processes of mussels, leading to acute or chronic stress, reduced fitness and populations, and reduced ecosystem services.

Excessive suspended sediments that include contaminants can be efficiently captured and often efficiently bioaccumulated by mussels, leading to acute or chronic stress, reduced fitness and populations, and reduced ecosystem services, as well as facilitating contaminant entry to aquatic food webs.

Brines, Contaminants, Water Quality

Freshwater mussels are very sensitive to water quality and most classes of contaminants. Contaminant exposure can be particle-mediated (discussed above) or direct via dissolved compounds or attributes associated with the water (discussed here.) Because freshwater mussels feed and respire by filtering large volumes of water across many thin tissue layers (e.g., mantel, gills) they are highly exposed to changes in water quality. Therefore, dissolved toxins (e.g. heavy metals, TDS, biocides) are rapidly taken up by direct absorption (Russell and Gobas 1989, Metcalfe Smith et al. 1996, Riedel et al. 1998) and indirectly via the food (Wikfors et al. 1994).

Mussels can temporarily (hours to days) avoid some contaminants or poor water quality (e.g. low dissolved oxygen) by closing their shells, if the contaminant is of a type and at a concentration that the animal can detect.

Suboptimal water quality (e.g. high conductivity) or the presence of waterborne (dissolved) contaminants might cause acute toxicity and mortality by exceeding mussel tolerance levels.

Suboptimal water quality or the presence of contaminants will impart chronic toxicity to mussels, leading to decreased productivity or reproductive output due to stress or bioaccumulation of contaminants in soft tissues.

Stressed mussels consume more oxygen, especially at higher temperatures, potentially contributing to low DO in some deeper areas.

Physiological impairment due to acute or chronic toxicity from chemical or high solute exposure will reduce population-level ecosystem services, especially biofiltration services.

Ecological Flows

As aquatic organisms, freshwater mussels can survive only brief exposure to the atmosphere, particularly when high temperatures rapidly desiccate exposed mussels or when low air temperatures quickly freeze exposed mussels. Very low water can buffer temperature changes to some extent but low water velocity also allows for greater solar exposure in the summer and increased temperature (and decreases in dissolved oxygen) resulting in stress and mortality.

Similarly, low water during colder periods can result in the formation of ice, which in shallow water can reach the substrate, killing any mussels that freeze.

Riverine mussel species depend upon flow for not only food and oxygen but also to maintain water quality and shape the physical habitat. For example, reduced flow increases the likelihood of silt deposition in areas that may typically have velocity that precludes deposition, and contaminants in the water are increasingly concentrated during low flow events.

Sustained low flows, which could result from unregulated withdrawals from headwater streams, can alter quality and quantity of food, causing stress and reproductive failure for mussels.

Low flows can interfere with mussel reproduction if fish hosts are unavailable for mussel larvae, depending on seasonality.

Any physiological impairment due to extreme low or high temperatures associated with low flows or reduced habitable bottom will reduce population-level ecosystem services, especially biofiltration services.

<u>Invasive Species</u>

Activities that result in transfer of water between watersheds have also resulted in the transfer of exotic or invasive species that can cause direct mortality of freshwater mussels through predation, toxicity, and disease or through competition for food or habitat. Resource management agencies have taken great pains in recent years to educate the public and institute practices to prevent the accidental spread of invasive species by anglers, boaters and other recreationists.

Once established in a waterway, zebra mussel populations can become extremely abundant, directly competing with native mussels for food and rapidly covering any exposed surface of a mussel shell. In some locations, populations of native freshwater mussels have been severely reduced, or eliminated, after zebra mussel colonization that altered substrate, flow, and food availability.

In the fall of 2009, Dunkard Creek, a tributary of the Monongahela River located along the border of southwestern Pennsylvania and West Virginia experienced a massive aquatic kill affecting native freshwater mussels, fish and salamanders in a 43-mile reach of the Creek. The kill was associated with a spike in conductivity that may have caused direct mortality of freshwater mussels, but which also contributed to the bloom of an invasive marine alga *Prymnesium parvum* or "golden alga", a species that proliferates in saline waters more typical of coastal Texas than the Appalachian Mountains of Pennsylvania. Golden algae produce a toxin fatal to other aquatic organisms. The species had never been observed in Pennsylvania waters before the Dunkard Creek aquatic kill but is known to thrive at the higher TDS concentrations that are often associated with mining and drilling activity. Its presence in state waters makes spread of the species to other surface waters of the state highly likely. Transfer of water between basins increases the risk that invasive species like golden algae and zebra mussel will also be inadvertently introduced to the Delaware Basin. Once established, invasive species are very difficult or impossible to remove.

Loss of Forest Cover

Some mussel species depend on leaf litter inputs for their nutrition. Forest loss or fragmentation, especially in areas near streams and rivers, has the potential to significantly impair food quality and quantity as well as degrade stream habitats for mussels by altering nutritional conditions as well as physical and chemical habitat conditions. In streams of southeast Pennsylvania, for example, the only remaining mussel beds are found within heavily forested areas of watersheds such as the Brandywine and Ridley Creeks – mussel abundance decreases dramatically in stream reaches above and below forested segments.

Loss or fragmentation of forests near streams and rivers can impair mussels by altering nutrition support and degrading habitats, thereby reducing mussel populations and ecosystem services.

V. Special Considerations – Dwarf Wedgemussels

The federal endangered dwarf wedgemussel (*Alasmidonta heterodon*) is sensitive to many of the same threats described above for other native species of freshwater mussels. Siltation, hydrologic changes, and contaminants are among the threats to the species survival cited at the time it was listed in 1990 (55 FR 9447 9451; U.S. Fish and Wildlife Service 1993).

Dwarf wedgemussels have characteristics that likely increase their susceptibility to these factors. First, the species is small compared to most other freshwater mussel species, (in the range of about an inch in length); therefore, relatively minor siltation events can deposit a smothering silt layer that reaches a depth that animals cannot push above.

Second, although they require flowing water and occur in a diversity of habitats from small streams to large rivers, dwarf wedgemussel are a thin shelled species that could be easily transported during a scour event. Like many freshwater mussels, dwarf wedgemussel populations tend to occur in areas protected from high-flow events, such as side channels of larger rivers and lower gradient streams. These low to medium velocity areas tend to have finer particle size substrates. Infiltration of relatively smaller amounts of silt between sands and smaller gravel particles can quickly hinder interstitial flow.

In the Delaware River this microhabitat preferred by dwarf wedgemussels tends to be away from the main channel, and therefore it is very susceptible to low flow exposure and associated changes in temperature. The seasonality of low flow and temperature rise may also be critical for dwarf wedgemussel reproduction and nutrition since freshwater mussels require specific food conditions for reproductive conditioning.

Dwarf wedgemussels are sensitive to all of the factors listed in Sections I-IV and potentially more susceptible than other mussel species to sedimentation, low flow, and temperature extremes.

VI. Management Implications for Natural Gas Development

It is our opinion that natural gas drilling activities, including the construction of natural gas exploratory wells, pose a substantial risk to mussel populations in the Special Protection Waters of the Delaware River Basin but that this risk can be reduced through the mandatory use of protective management practices of the types set forth below:

A. Consistent use of avoidance and minimization measures across the supporting watershed in three states to reduce the risks that siltation, spills or other releases of contaminants, flow changes and the spread of invasive species could adversely affect mussel populations, including the federally listed dwarf wedgemussels that inhabit the upper Delaware River.

B. Implementation of stormwater management and erosion and sedimentation control practices to help minimize sources of sediment during and after construction of natural gas well pads, wells and impoundments.

C. Monitoring of water quality, flow conditions, and invasive species in potentially affected areas before, during and after project construction in order to identify where preventive measures may have failed, where they were effective, and where mitigation or restoration measures are warranted.

D. Monitoring of the diversity, fitness and abundance of freshwater mussel assemblages in potentially affected areas.

References

Aldridge, D.W., B.S. Payne and A.C. Miller. 1987. The effects of intermittent exposure to suspended solids and turbulence on three species of freshwater mussels. Environmental Pollution 45:17-28.

Bauer, G. and K. Wächtler. 2001. Environmental relationships of naiads: threats, impact on the ecosystem, indicator function. In: Ecological Studies, Vol. 145, G. Bauer and K. Wächtler (eds.) Ecology and Evolution of the Freshwater Mussels Unionoida. Springer-Verlag, Berlin.

Dame, R.F. 1996. Ecology of Marine Bivalves: An Ecosystem Approach. CRC Press, New York.

Ellis, M. M. 1936. Erosion silt as a factor in aquatic environments. Ecology 17: 29-42.

Harman, W.N. 1974. The effects of reservoir construction and channelization on the mollusks of the upper Delaware watershed. Bulletin of the American Malacological Union for 1974:12-14.

Howard, J.K. and K.M. Cuffey. 2005. Factors controlling the age structure of *Margaritifera falcata* in two California streams. Journal of the North American Benthological Society.

Kreeger, D.A. 2004. Beyond biodiversity: the conservation and propagation of native mussel biomass for ecosystem services. Abstract In: Proceedings of the 2nd Annual Freshwater Mussels of the Pacific Northwest Symposium. Pacific Northwest Native Freshwater Mussel Workgroup, Vancouver WA. Pp. 11-12. http://columbiariver.fws.gov/mwg/mussel2004ws/2004_Proceedings.pdf (abstract)

Kreeger, D., D. Raksany and C. Gatenby. 2002. Variability in condition index and tissue biochemistry of Elliptio complanata held in the field and laboratory. J. Shellfish Res. 21(1): 366.

Kreeger, D.A. and J. Kraeuter. 2010. Ecologically significant bivalve molluscs of the Delaware Estuary. Appendix N, In: Climate Change and the Delaware Estuary: Three Case Studies in Vulnerability Assessment and Adaptation Planning. Partnership for the Delaware Estuary, PDE Report No. 10-01. 117 pp. http://www.delawareestuary.org/science_projects_climate_ready_products.asp

Lellis, W.A. 2001. Freshwater Mussel Survey of the Delaware Scenic and Recreational River, Qualitative Survey 2000. Report to the National Park Service, February 20, 2001. 6 pp plus appendices.

Lellis, W.A. 2002. Freshwater Mussel Survey of the Delaware Water Gap National Recreation Area, Qualitative Survey 2001. Report to the National Park Service, March 8, 2002. 12 pp plus appendices.

Martel P., Kovacs T., Voss R. & Megraw S. 2003. Evaluation of caged freshwater mussels as an alternative method for environmental effects monitoring (EEM) studies. Environ Pollut 124[3]: 471-483.

McMahon, R. F. 1991. Mollusca: Bivalvia. In: J. H. Thorp and A. P. Covich (eds.), Ecology and Classification of Freshwater Invertebrates. Academic Press Inc., New York. pp. 315 397

MetcalfeSmith, J.L., Green, R.H., & Grapentine, L.C. 1996. Influence of biological factors on concentrations of metals in the tissues of freshwater mussels (Elliptio complanata and Lampsilis radiata radiata) from the St. Lawrence River. Can J Fisheries Aquat Sci, 53: 1996 219.

Ortmann, A. E. 1919. A monograph of the naiades of Pennsylvania. Part III. Systematic account of genera and species. Memoirs of the Carnegie Museum. 8(1):1-384.

Partnership for the Delaware Estuary . 2008. State of the Estuary Report. PDE Report #08-0. 36 Pusch, M., J. Siefert, and N. Walz. 2001. Filtration and respiration rates of two unionid species and their impact on the water quality of a lowland river. pp. 317-326 in G. Bauer and K. Wächtler (eds.). Ecology and evolution of the freshwater mussels Unionoida. Ecological Studies Vol. 145., Springer-Verlag, Berlin. 394 pp.

Riedel, G.F., G.R. Abbe and J.G. Sanders. 1998. Temporal and spatial variations of trace metal concentrations in oysters from the Patuxent River, Maryland. Estuaries 21(3):423-434.

Russell, R.W., & Gobas, F.A.P.C. 1989. Calibration of the Freshwater mussel, Elliptio complanata, for Quantitative Biomonitoring of Hexachlorobenzene and Octachlorobenzene in Aquatic systems. Bull Environ Contam Toxicol, 43: 576 582.

U.S. Fish and Wildlife Service. 1993. Dwarf Wedge Mussel (Alasmidonta heterodon) Recovery Plan. Hadley, Massachusetts. 52 pp.

Endangered and Threatened Wildlife and Plants; Determination of Endangered Status for the Dwarf Wedge Mussel. 55 Federal Register 50 (14 March 1900), pp. 9447 - 9451.Tyrrell, M. and D.J. Hornbach. 1998. Selective predation by muskrats on freshwater mussels in 2 Minnesota rivers. Journal of The North American Benthological Society 17:301-310.

Vanni, M.J. 2002. Nutrient cycling by animals in freshwater ecosystems. Annual Review of Ecological Systems 33:341-370.

van Tets, G.F. 1994. Do cormorants eat freshwater mussels? If not what does? EMU 93:127-8.

Vaughn, Caryn C. and Hakenkamp, Christine C. 2001. The functional role of burrowing bivalves in freshwater ecosystems. Freshwater Biology 46:1431-1446.

Vaughn CC, Gido KB, and Spooner DE. 2004. Ecosystem processes performed by unionid mussels in stream mesocosms: species roles and effects of abundance. Hydrobiologia 527 (1): 35-47

Wikfors, G.H., J.W. Twarog Jr., G.E. Ferris, B.C. Smith and R. Ukeles. 1994. Survival and growth of post-set oysters and clams on diets of cadmium-contaminated microalgal cultures. Mar. Env. Res. 37:257-281.

Williams, J. D., M. L. Warren, K. S. Cummings, J. L. Harris, and R. J. Neves. 1993. Conservation status of freshwater mussels of the United States and Canada. Fisheries 18:6-22.