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# Water Quality and Wetland Function in the Northern Prairie Pothole Region


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## Introduction

Wetlands are unique areas that have characteristics of both land and water, as the name implies. Wetlands are considered transitional areas between aquatic systems and upland terrestrial systems. They can be inundated with water for long periods of time, or can lack free water on the surface for lengthy periods. Ponding and drying often is a regular, annual cycle of wetness.

The transitional nature of wetlands is characterized as a zone of dynamic water movement. Water levels may fluctuate from a few feet above to several feet below the surface in a single season. The fluctuation in soil moisture content and aeration is highly variable, compared with aquatic systems that are saturated continuously or upland terrestrial systems where soils never are saturated. Cycles of wetness may occur in relatively predictable seasonal patterns or longer-term climatic patterns. However, within these patterns, the variability of weather also contributes to extreme conditions of wetness or dryness within a given wetland basin.

The term wetland is somewhat misleading because it suggests a narrow range of properties and functions within wet areas. In reality, wetland areas are transitional zones that exhibit extremely different properties and functions that vary with both space and time. Determining the relationship between wetland function and water quality within the context of an ecological system or landscape requires understanding of the range of chemical, physical and biological processes that likely are to occur. Soil properties of the wet-extreme are very different from the dry-extreme. Within a landscape context, wetland soil properties and processes vary along a continuum, often in a predictable pattern. The processes that characterize the wetland extremes generally are coupled and need to be viewed in tandem to fully appreciate wetland function, particularly as it relates to water quality. For example, the wetter areas of a wetland allow conversion of nitrate to gaseous forms of nitrogen that are released into the atmosphere. However, drier areas of the same wetland will produce nitrate through mineralization of organic matter. The ultimate effect on nitrate levels in groundwater or surface water will depend on the balance of these two processes.

Wetlands have several major functions: 1) biologic diversity/integrity; 2) water storage; 3) water exchange between surface water and groundwater; 4) surface water filtration; 5) vapor and gas exchange with the atmosphere; 6) chemical attenuation and transformation. The capacity of wetland systems to perform these functions has a direct bearing on water quality.

Natural wetlands are quite variable, thus the capacity of a given wetland to perform a given function also is variable. To help us understand the range in wetland properties and function, wetland classification schemes have been developed. Addressing the issue from the perspective of the more common classification systems is helpful to understand the relationships between wetland function and water quality.

# Wetland Classification and Water Quality

Cowardin et al. (1979) developed a classification for wetlands and aquatic systems in the United States that still is in use today. The Cowardin classification system is composed of five major categories that are subdivided into many subclasses. Wetlands fall into the major category of "Palustrine." In North Dakota, the palustrine systems often occur adjacent to the major categories, "Riverine" and "Lacustrine," which represent the aquatic habitats of streams and lakes, respectively.

The stream channel separates the stream and wetland systems. A somewhat arbitrary depth of 6 feet has been used to separate aquatic systems of lakes from permanent wetlands with shallower water. Another arbitrary measure often used to separate lakes from wetlands is size. Areas of permanent water less than 20 acres generally are considered wetlands unless active wave cut features are present along the shore.

The wetlands of the palustrine system form a transitional zone between the uplands and aquatic systems that serves as a filter or buffer with respect to water quality. Water chemistry is one of the properties used to modify the wetland type. Salinity and pH are the two water chemistry parameters used to categorize wetlands (Tables 1 and 2).

Water salinity that exhibits extreme variability may be described by adding the prefix "poikilo" to the salinity class name, or vice versa, water salinity exhibiting little variability may be described by adding the prefix "homio" to the salinity class name.

Stewart and Kantrud (1972) developed a classification system specifically for ponds and lakes in glaciated prairies. This system was the basis, in part, for Cowardin's classification and remains in use today. It probably is referred to most often when wetlands are categorized in the northern prairie pothole region (NPPR). The parameters used for classification were permanence of standing water and salinity as correlated to plant communities. Seven different vegetation zones were recognized, as shown in Table 3. Areas greater than 50 acres were considered lakes. No attempt was made to differentiate aquatic from wetland systems using water depth. However, "open water" was one of the seven vegetation zones and is considered to have relatively deep water that would be a characteristic of the aquatic system.

The Stewart and Kantrud classification recognized that changes in water level and cultivation affect plant communities; therefore, drawdown and tillage phases were defined for certain wetland classes. The plant community also reflects water salinity and is recognized as a subclass (Table 4) similar to the Cowardin system.

Both of the previously described wetland classifications emphasize indicators of wetness, as one would expect. Wetness is an aspect of hydrology, but lacks any indication

**Table 1. Cowardin system wetland water salinity classes.**

| Modifier | EC (dS/m) |
|---|---|
| **Hypersaline** | **> 60** |
| Saline | 45 -60 |
| Near-saline | 30-45 |
| Moderately saline | 8-30 |
| Slightly saline | 0.8-8 |
| **Fresh** | **< 0.8** |

**Table 2. Cowardin system wetland water pH classes.**

| Modifier | pH |
|---|---|
| Acid | < 5.5 |
| Circumneutral | 5.5-7.4 |
| Alkaline | > 7.4 |

**Table 3. Stewart and Kantrud wetland classes.**

| Wetland class | Central vegetation zone | Common plant* |
|---|---|---|
| I-ephemeral | Low prairie | Kentucky bluegrass |
| II-temporary | Wet meadow | Fowl bluegrass |
| III-seasonal | Shallow marsh | Slough sedge |
| IV-semipermanent | Deep marsh | Cattail |
| V-permanent | Open water | Western widgeongrass |
| VI-alkali | Intermittent alkali | Western widgeongrass/ salt flat |
| VII-fen | Alkaline bog | Aquatic sedge |

*General plant indicators that may be present, depending on salinity or disturbance of the direction or type of water flow. Understanding of water flow can be helpful in determining important wetland processes and estimating the capacity to perform those processes or functions. Arndt and Richardson (1988) combined knowledge of groundwater flow in the northern prairie pothole region with the Stewart and Kantrud classification. They found that soil chemical indicators, such as salinity, could be used to classify wetlands into three major groundwater flow categories (Figure. 1). Groundwater flow can be predominantly away from (recharge) or into (discharge) the wetland basin. When groundwater flows away from the wetland basin and is balanced by flow into the basin, a flow-through wetland exists.

The relationship among wetland hydrology, soils and the Stewart and Kantrud system is illustrated with a summary of the data gathered by Arndt and Richardson (1988) (Table 5).

Salinity is an obvious water quality characteristic that influences the wetland environment. It is relatively predictable and has been incorporated in the major wetland classification schemes. Wetland salinity by itself probably is not a critical water quality issue. However, because of the connection among wetlands, streams, lakes and aquifers, it may be a first indicator of possible changes to these water resources.

The need to predict the fate of various chemicals as they pass through the wetland environment is what elevates the importance classification systems. Chemical transport processes are dependant on the wetland conditions that are defined and categorized in a classification system. Classification is the basis for wetland inventory and monitoring activities that help predict chemical transformations and transport on a landscape scale. Effective management of our natural resources depends on accurate assessment of wetland processes and the functions they serve. In other words, different classes of wetlands have different functions with respect to water quality, and these differences need to be recognized in our management strategies.

**Table 4. Stewart and Kantrud wetland salinity subclasses**

| Subclass designation | EC (dS/m) |
|---|---|
| **Saline** | **>45** |
| E-Subsaline | 15-40 |
| D-Brackish | 5-15 |
| C-Moderately brackish | 2-5 |
| B-Slightly brackish | 0.5-2 |
| **A-Fresh** | **< 0.5** |

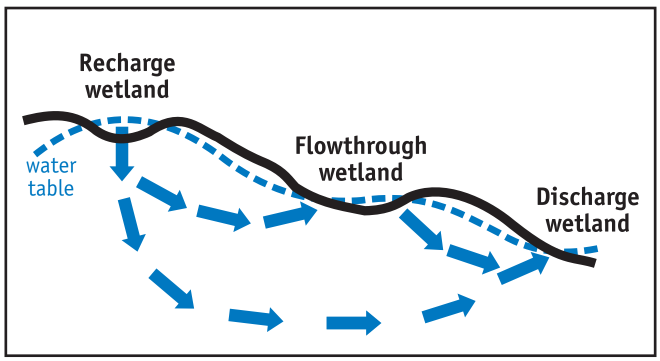



**Figure 1. Recharge-Flow-through-Discharge**

**Table 5. Soil properties in wetlands with different groundwater hydrology**

| Wetland class | Pond salinity | Soil class | Soil salinity dS/m | Calcite % | Gypsum % |
|---|---|---|---|---|---|
| **Recharge hydrology** | | | | | |
| Seasonal | Fresh | Argiaquolls and Haplaquolls | 0.4 –0.6 | 0 | 0 |
| **Flow-through hydrology** | | | | | |
| Seasonal – Semipermanent | Slightly – moderately brackish | Calciaquolls and Haplaquolls | 2 – 8 | 3 - 16 | .02 - 15 |
| **Discharge hydrology** | | | | | |
| Semipermanent | Subsaline | Fluvaquents and Haplaquolls | 11 – 26 | 7 – 11 | 2 - 6 |

Note: Soil samples were collected from the upper 21 inches in the wet meadow and shallow marsh vegetation zones.

# Water Movement and Water Quality

To understand the relationship between wetlands and water quality of streams, lakes and aquifers, the flow of water to and from the wetlands must be viewed from the perspective of the whole landscape. The permeability of the surface soil affects water runoff from areas adjacent to wetlands. Under prairie vegetation, soils have relatively higher amounts of organic matter, greater aggregate stability and a higher percentage of macropores, compared with cultivated fields. Because of this, prairie soils have higher infiltration rate capacities and less potential to generate surface runoff to wetlands. Under these conditions, the predominant source of water for wetland ponds is precipitation that falls directly on the pond.

The major impacts to wetlands adjacent to cultivated uplands are increased pond levels immediately after rainfall events, increased sedimentation and increased nutrients. From landscape analyses, we know wetlands occur in positions that function as natural filters or sediment basins. Considering the natural role wetlands play as an environmental filter, what are the water quality implications related to wetlands in cultivated areas? The answer is complicated by the fact that different wetland classes provide different functions on the landscape. Also, impacts of surface runoff from cultivated areas are due to increased rates of natural processes, not new phenomenon. If the rate of input of sediment, organic matter, nutrients and other natural or manmade contaminants exceeds the functional capacity of a given wetland to absorb and transform, then one would expect contaminants to be passed along to adjacent streams or lakes. The question is not if these things are getting into wetlands, because they are and always will. The real question is, when does the rate of input exceed the functional capacity?

An important point regarding wetlands and water quality is the proximity to aquatic systems (streams and lakes). It is a critical factor that must be addressed when prioritizing management activities. Wetlands adjacent to streams and lakes will provide the most immediate water quality benefits. If adjacent wetlands lose their functional capacity to absorb and transform contaminants, impacts to streams and lakes would be expected shortly thereafter. Evidence shows that isolated wetlands also are connected to other water resources, but in a more subtle and indirect fashion. The long-term loss of isolated wetlands actually may have greater consequences on other water resources than the loss of adjacent wetlands.

## The Surface Water-Groundwater Connection

The discussion of water flow, wetlands and water quality should not proceed too far before interjecting the connection between surface water and groundwater. The concept of recharge-flow-through-discharge already has been introduced. Soil infiltration controls surface water flow in all three of these groundwater flow scenarios discussed above. However, the interconnection between surface water flow and groundwater flow is relatively different for each of the three wetland-hydrology scenarios. In turn, the implications for water quality also are quite different.

The ratio between the wetland catchment that contributes runoff and the size of the wetland basin decreases from an average of about 8 for recharge wetlands to about 2 for discharge wetlands. The relatively larger catchments for recharge wetlands emphasizes the dominance of surface water flow to their basins, which are relatively smaller, compared with flow-through and discharge wetlands. The leached nature of the soils in recharge basins as shown earlier (Table 5) indicates that pooled surface water in recharge basins eventually percolates through the wetland soil to the groundwater. This is the dominant groundwater recharge process in the prairie pothole region and has been coined as "depression focused recharge."

Groundwater flow is mostly in the vertical direction immediately beneath recharge wetlands, but eventually begins to turn laterally with distance and feeds into flow-through wetlands and finally discharge wetlands (Figure 1). The horizontal permeability of the till generally is no greater than in the vertical direction because of the relatively fine texture, high bulk density and lack of horizontal stratification. This means that directly beneath recharge wetlands, groundwater removes salts to depths of nearly 30 feet. However, little salt removal occurs beneath upland areas only short distances from where focused recharge occurs. Groundwater flow then slowly redistributes leached salts from the beneath the recharge wetland to flow-through and discharge wetlands. Salts become more concentrated in pond water and soils of wetlands that receive proportionately greater contributions of groundwater and have no outflow either to groundwater or surface water (Table 5). Discharge wetlands essentially are evaporation basins that have such high loads of salts that some have been mined commercially. The rate of salt transport to wetlands is substantially greater when groundwater flow encounters geologic materials with high horizontal permeability, such as coarse-textured sands and gravels. The highest levels of salinity generally are associated with discharge wetlands that occur in glacial outwash.

Two salient points must be made regarding the relationship between water quality and groundwater hydrologic regime in the NPPR. First, groundwater recharge is focused in depressions, some of which do not meet jurisdictional criteria for wetland designation. Large numbers of these areas (class I – III wetlands) are farmed actively. Because these areas recharge groundwater, they have the potential to transmit contaminants, and recent studies show they do indeed influence nitrate concentrations in shallow aquifers. Farming practices that influence the balance between water infiltration and runoff will affect groundwater recharge. Second, groundwater recharge is closely coupled with shallow groundwater discharge to lower-lying wetlands (class IV-VII). In this case, the main water quality issue related to groundwater is the concentration of salts in the pond water. Changes to the hydrologic system that increase groundwater discharge or impede either surface and/or groundwater flow-through will result in increased salinization in these wetlands. Consequently, adjacent aquatic systems of streams and lakes also would be expected to exhibit higher salt loads. Specifically, sodium concentrations would be of concern.

## Hillslope Interflow and Wetlands

In the NPPR, the importance of transitory lateral flow or interflow from adjacent hill slopes to adjacent wetlands is open to debate. Interflow is a well-established phenomenon that regularly occurs through hillslope soils in more humid environments, being controlled by a combination of antecedent moisture, infiltration capacity and horizontal hydraulic conductivity. Physical differences in soil horizons have been observed to play an important role in this type of groundwater flow. Conditions for interflow are not as likely to occur in drier environments largely due to lower potential for high levels of antecedent moisture. However, evidence for interflow through hillslopes under prairie vegetation in the NPPR does exist and its relative importance to surficial hydrology probably has been underestimated.

Saline seepage is a well-documented hydrologic process that occurs in the northern Great Plains (Figure 2) and is similar to hillslope interflow. Excess water that escapes vertically through the soil profile on summer-fallowed land initiates the seepage process. This water is diverted laterally by impermeable geologic strata and picks up

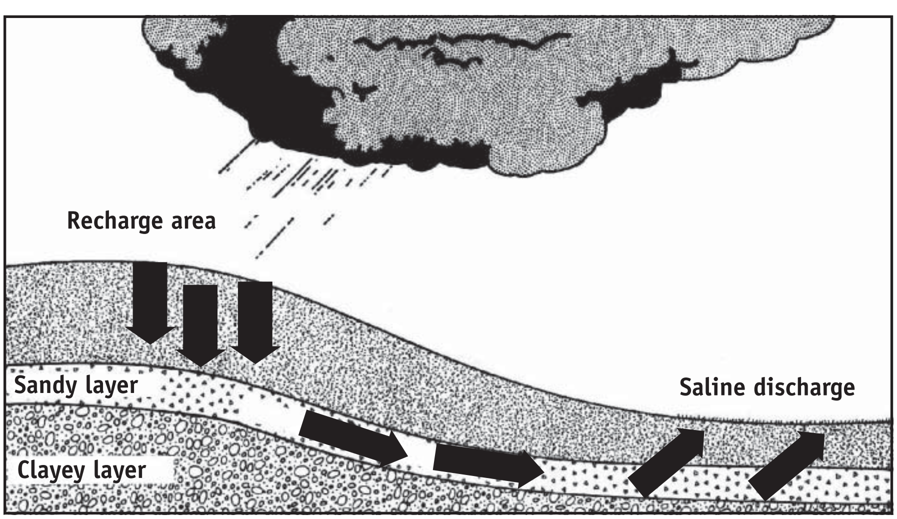



**Figure 2. Hillslope saline seepage**

soluble salts. It moves back toward the soil surface on hillslopes that truncate the impermeable geologic strata, where it evaporates and deposits its load of salts. The hydrologic change is directly related to a drastic change of land use in the upland soils (prairie to a cultivated crop – summer-fallow rotation). Although summer fallow contributes to lower infiltration, it causes increased percolation losses due to the lack of plant transpiration during the fallow period. The capacity of the soil to store water in the rooting zone is exceeded by the amount of water that infiltrates. The saline seepage phenomenon demonstrates that changes to the soil condition in upland areas can have significant impact on the hydrology in areas further down-slope.

Differences in the period of ponding between wetlands of the same class receiving the same amount of rainfall have been explained by differences in interflow related to soil management. The correlation between reduced soil aggregate stability, decreased infiltration capacity, and increased surface runoff and erosion is well-known. Soil conditions in adjacent uplands that promote runoff to wetlands decrease the potential for subsurface interflow. Wetlands with an active interflow component, compared with those filled solely by runoff, will exhibit lower ponding levels that exist for longer periods of time. Greater sediment loading in runoff-fed wetlands, compared with wetlands fed by interflow, is the primary difference related to water quality. However, the slower but more continuous contribution of interflow water also contributes to the maintenance of class VII wetlands or fens. Short periods of high-level ponding in runoff-fed wetland basins accompanied by long periods of dry conditions shifts the wetland environment to one of greater chemical oxidation, e.g., greater release of carbon dioxide (CO2) and nutrients.

# Wetland Processes and Water Quality

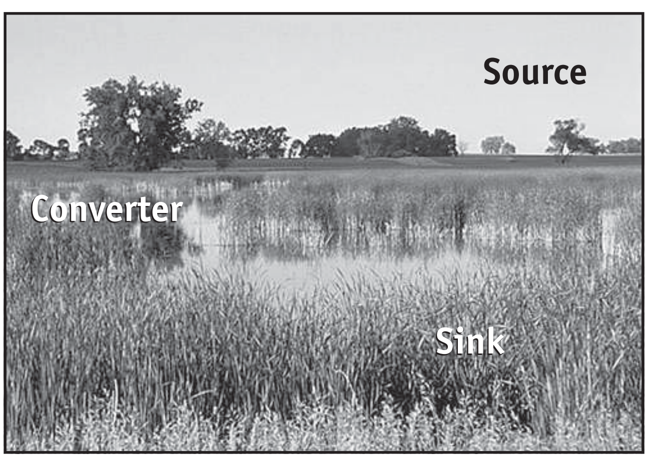
The wetlands and water quality discussion began with classification and hydrology for a good reason. When addressing this subject, having some understanding regarding the range of conditions commonly used to define wetlands is absolutely necessary. The discussion on wetland classification was intended to provide that perspective with an organized structure. The discussion on hydrology followed because it determines when, where and how much of the key ingredient, water, is delivered. Water quality depends not only on those things that are transported with water to wetlands via different hydrologic pathways, but it also depends on those things that are transformed within and transported out of wetlands (Figure 3). The presence of water or lack of it influences the processes, such as oxidation-reduction, that control chemical transformations and the mobilization/immobilization balance. In general, when the balance swings in favor of mobilization, excessive amounts of the mobile chemical may jeopardize water quality. Emphasis is on the concept of balance because many transformation processes alternate relatively rapidly between mobilization and immobilization or are operating contemporaneously due to spatial variability within the wetland.

## Sediment

Wetlands act as natural filters for sediment. Erosion and sedimentation are natural, ongoing geologic processes that explain the textural continuum of coarse to fine material proceeding into the wetland from the edge. Geologic rates of sedimentation are relatively slow and allow soil-forming processes to incorporate recent sediment into the existing soil profile of horizons. However, sedimentation rates may exceed natural rates of soil formation when increased by accelerated erosion from adjacent uplands. Water quality impacts begin with the loss of capacity for wetland soils to stabilize sediment deposits adequately. The filter no longer functions to protect adjacent streams and lakes. Suspended sediment levels increase, which contributes to warmer water with less dissolved oxygen. Associated effects are related to organic matter, nutrients, pesticides and other chemicals that are intricately associated with chemically active clay-sized particles. Rather than being transformed in the wetland, they pass through to streams and lakes, where they contribute to eutrophication or conditions toxic to aquatic organisms.

Secondary impacts of excessive sedimentation in wetlands are related to materials that are substantially different than the organic-rich A-horizon of most wetland soils. Organic matter stabilizes the soil surface by promoting

$CO_2$ ➔ plants and soil
Nutrients ➔ plants and soil
Manmade organics ➔ $CO_2$




$NO_3$ ➔ nitrogen gas ($NO_2$, $N_2$)
Soil organic matter ➔ methane gas ($CH_4$)
Sulfate salts ➔ sulfur gas ($H_2S$)
Methyl mercury ➔ mercury gas ($Hg_2$)

Sediments
Nutrients (e.g. P, N)
Salts (e.g. sulfates)
Heavy metals (e.g. mercury)
Manmade organics (e.g. pesticides, PCPs, dioxins)

**Figure 3. Environmental role of a semi-permanent wetland**

aggregation, soil structure and macroporosity. It helps create an environment for rapid exchange of chemicals and serves as a source of energy and nutrients for biological life cycles. Thick layers of recent sediment deposits generally lack the soil structure found in natural soils, thus reducing the natural capacity for chemical transformation. This may lead to increased levels of mobile chemicals available for transport to adjacent streams and lakes or aquifers below class I – III wetlands.

## Carbon and Organic Matter

The wetland environment usually is a system of high plant productivity (sequestration of $CO2$) and low decomposition due to the anaerobic conditions that saturated soils create. Although wetlands occupy only 6 percent of the world's surface, they contain an estimated 14 percent of the terrestrial carbon pool. Stored organic carbon in wetlands is transformed and released as methane gas ($CH4$) through anaerobic oxidation. Therefore, wetlands serve as both a sink and source for atmospheric carbon.

As mentioned before, organic matter serves to stabilize soil aggregates and promotes structural integrity that is important to water movement through soils. It also is a source for nutrients and energy required for biotic growth. Organic matter exerts a positive influence on wetland soils' capacity to transform chemicals. However, when organic matter is transferred beyond the wetland boundary, it has negative impacts to aquatic environments. Transport of organic matter in water may occur as a dissolved or suspended phase. Organic matter in an aquatic environment provides the energy for microorganisms, such as bacteria, to thrive. Microbial oxidation of organic matter releases energy to the microorganisms and consumes dissolved oxygen (biological oxygen demand, or BOD). Aquatic organisms, such as fish, need relatively high levels of dissolved oxygen, so high levels of BOD will have a negative effect on their survival. Organic matter also is a source of nutrients that further contribute to excessive growth of lower groups of aquatic organisms, such as algae. Maintenance of a wetland's ability to assimilate organic matter depends on the rate at which it is added. As with sediment, the functional capacity of a wetland will depend on runoff and erosion from adjacent upland soils.

Dissolved organic matter may or may not be utilized easily as an energy source. Some soluble forms of organic matter, such as tannins, are quite resistant to biodegradation and give the water a yellow to dark brown color. Biologic decomposition of organic matter is greater under oxidizing conditions, compared with conditions of low to no oxygen. Under these circumstances, large amounts of organic matter in various stages of decomposition may accumulate. Wetland environments that have developed under exceptionally high rates of groundwater inflow (springs) are characterized by soils that are composed predominantly of organic matter. The organic soils often occur as a "floating" mass above the free water surface and are classified as fens (class VII). The water in these systems is alkaline and has high amounts of calcium. Fens are an uncommon type of wetland on the prairies and often have rare and endangered plant species due to their unique niche in the prairie environment.

## Nutrients: Nitrogen

Nitrogen is distributed among the atmospheric, biologic, geologic and hydrologic pools. The processes of nitrogen exchange among these pools are commonly referred to as the "nitrogen cycle." The most active pool of nitrogen transformation is the biologic, where nitrogen is a component of myriad organic compounds. However, the amount of nitrogen in this pool at any given time accounts for only 2 percent of the Earth's total nitrogen.

Oxidation of the organic matter releases inorganic forms of nitrogen and is referred to as mineralization. The reverse of mineralization occurs when inorganic nitrogen is incorporated into biologic tissue in a reduced-oxidation state and is referred to as immobilization. Both of these processes involve the exchange of eight electrons that results in gaseous, mineral and organic compounds composed of nitrogen with different oxidation states (Table 6). Mineralization and immobilization occur simultaneously and provide continuous movement between the organic and inorganic pools of nitrogen.

Mineralization of organic nitrogen includes two processes, ammonification and nitrification. Ammonification releases ammonia gas that quickly is hydrolyzed to the ammonium ion. Nitrification occurs when the ammonium ion is oxidized through a series of reactions to nitrate. Nitrate is an extremely active chemical in the environment because of its high availability for biologic uptake and mobility. Although nitrification is not the only process that contributes nitrate to the soil, it is the predominant process. Because many types of reactions and organisms are involved with mineralization and immobilization, changes in environmental conditions have varying impacts on the forms and quantity of soil nitrogen at any given time.

**Table 6. Natural forms of nitrogen in the environment**

| N form | Chemical name | Oxidation state of N |
|---|---|---|
| $-CH_2-NH_2$ | Organic N | -3 |
| $NH^{4+}$ | Ammonium ion | -3 |
| $NH_3$ | Ammonia | -3 |
| $N_2$ | Dinitrogen gas | 0 |
| $NO_2$ | Nitrous oxide gas | +1 |
| $NO_{2-}$ | Nitrite ion | +3 |
| $NO_{3-}$ | Nitrate ion | +5 |

The major source of nitrogen that accumulates in soils is biological fixation of elemental-N ($N_2$) from the atmosphere. Organisms capable of fixing $N_2$ are thought to have developed early in Earth's history. The symbiotic relationship between legumes'  Rhizobia bacteria is the culmination of millions of years of evolution. Legumes have the potential to fix as much as 500 pounds/acre/year of nitrogen. Nonsymbiotic organisms, such as Azotobacter and Clostridia bacteria, and autotrophic blue-green algae also fix atmospheric $N_2$. Blue-green algae synthesize toxins that have potential for serious impacts to aquatic systems when rapid growth (algal bloom) is triggered.

When oxygen is depleted in the soil, reduction of nitrate by anaerobic bacteria is called denitrification. The process results in volatilization of nitrous oxide ($N_2O$) and $N_2$ if the reaction is completed. Through volatilization of $N_2O$ and $N_2$, the denitrification process removes nitrogen from soil environment, particularly in wetlands. Having denitrification and nitrification occur simultaneously is not uncommon in a soil profile with extreme spatial variation in organic material and oxygen content. Denitrification also depends on the presence of an oxidizable substrate to furnish the energy that denitrifying bacteria require. Organic carbon usually serves as the source of energy in the denitrification process, but in some cases, other chemicals such as iron sulfide or pyrite also may serve that role. The process of denitrification, coupled with plant uptake of nitrate in wetlands, make these systems powerful natural tools for environmental control of nitrogen.

Secondary chemical reactions linked to the denitrification process also have water quality implications. If sulfate produced by denitrification in the deeper part of the wetland sediments moves upward into the wetland soil, it will be reduced to hydrogen sulfide gas. The sodium and calcium associated with the sulfate are converted to carbonatic salts. A relative excess of sodium, compared to calcium ions, can lead to the formation of sodium carbonate salts that are highly corrosive due to a pH often well above 8.5.

In addition to $N_2O$ and $N_2$ produced by denitrification, ammonia also may be produced under highly reduced conditions in some wetland soils. If ammonification becomes the dominant process, conditions of high temperature, high pH and low cation exchange capacity will allow toxic quantities of dissolved ammonia to persist.

Nitrogen levels in NPPR wetlands, lakes and tributaries have been observed to vary seasonally. Generally the highest concentrations of nitrites and nitrates are found during spring runoff. These concentrations subside substantially by biological activity as temperatures increase later in the spring and summer. Total nitrogen concentrations in NPPR lakes are lowest in the fall, increase in the winter, remain the same or decrease in the spring and increase in the summer. The periods of highest total nitrogen concentrations are the summer and winter. In the summer, the predominant form of nitrogen is organic due to flourishing populations of aquatic organisms. In the winter, the predominant form of nitrogen is ammonia. This is because decomposition of organic material only proceeds through the ammonification step of mineralization due to the reduced environment. By the end of winter, toxic levels of ammonia may become a water quality problem, particularly in smaller lakes.

## Nutrients: Phosphorus

Phosphorus belongs to the same group (periodic chart) of elements as nitrogen. It shares many similarities with nitrogen, but also has distinct differences. Compared with nitrogen, phosphorus is substantially more abundant in earth materials. However, in just the soil, phosphorus is a minor constituent, averaging 0.05 percent. Phosphorus deficiency in plants is a common soil fertility problem. Phosphorus also is distinctly less mobile in the environment, compared with nitrogen. Phosphorus does not have gaseous phases that compare to nitrogen in terms of importance related to its environmental cycle. Phosphorus can exist in oxidation states ranging from –3 to +5 (Table 7). Unlike nitrogen, phosphorus does not shift readily between oxidation states, with the most prevalent state being +5.

Most phosphorus compounds (inorganic and organic) are derivatives of phosphoric acid ($H_3PO^4$). These compounds are formed in combination with the $PO_4^{-3}$ anion, commonly referred to as orthophosphate. $PO_4^{-3}$ exists in soils in an exchange continuum that runs from being weakly bound or adsorbed to being strongly bound within a crystal matrix, such as the mineral apatite [$Ca_5(PO_4)_3$]. Because of this, the availability and mobility of $PO_4^{-3}$ is subject to both exchange and chemical solubility reactions.

$PO_4^{-3}$ that is present in solution is the most mobile state and also available for uptake by plants and microorganisms. Adsorbed $PO_4^{-3}$ is associated with hydroxyl (OH) groups that are a chemical component of organic matter and many minerals. The bond is weak and readily releases $PO_4^{-3}$ to solution as replacement for soluble phosphorus that plants and microorganisms consume. Adsorbed $PO_4^{-3}$ often is referred to as "exchangeable" or "labile" phosphorus.

Some of the $PO_4^{-3}$ adsorbed on crystal lattices becomes incorporated into the crystal during a period of time with an accompanying loss of exchangeability. Crystalline-$PO_4^{-3}$ is released only during long periods of time due to the relative insolubility of phosphate minerals. Both exchange and solubility reactions are dependant on pH and redox potential; consequently, so is the release of $PO_4^{-3}$ to solution.

The term orthophosphate has become synonymous with soluble phosphate. This is somewhat of a misnomer that can lead to confusion when discussing water resource impacts from phosphorus. Most of the phosphate present in solution is in the ionic form of $HPO_4^{-2}$ or $H_2PO_4^{-1}$. Actually little soluble phosphorus occurs as $PO_4^{-3}$ under normal pHs. Technically, almost all insoluble phosphorus, both inorganic and organic, also is orthophosphate. Most organic forms of phosphorus, such as nucleic acids, nucleotides and sugar phosphates, are esters of phosphoric acid. Phosphorus is released when these organic chemicals are mineralized similarly to the release of nitrogen. Mineralization is an extremely important step in both the nitrogen and phosphorus cycles. In both cases, the chemical form released has the same oxidization state as the organic form. However, beyond this point, the nitrogen and phosphorus cycles diverge in similarity. Throughout its cycle, the chemical form of phosphorus remains basically the same as $PO_4^{-3}$, a component of many relatively insoluble compounds. Among these phosphorus-bearing materials, large differences in the release of $PO_4^{-3}$ to solution control environmental impacts to water resources.

**Table 7. Natural forms of phosphorus in the environment**

| P form | Chemical name | Oxidation state of P |
|---|---|---|
| $Ca_3P_2$ | calcium phosphide | -3 |
| $P^4$ | elemental phosphorus | 0 |
| $PO_3^{-3}$ (salt of $H_3PO_3$) | phosphite | +3 |
| $PCl_3$ | phosphorus trichloride | +3 |
| $PCl^5$ | phosphorus pentachloride | +5 |
| $PO_4^{-3}$ (salt of $H_3PO_4$) | orthophosphate | +5 |
| $PO_4^{-3}$ (ester of $H_3PO_4$) | organic orthophosphate | +5 |

Because both phosphorus and nitrogen are major nutrients required for biological growth, they work in tandem with respect to the process of eutrophication. In terms of biological activity, the nutrient in least supply will be the limiting factor for biological growth. Generally, aquatic systems with a ratio of N to P of less than 10:1 indicates an "N-limited" system and greater than 10:1 indicates a "P-limited" system. In other words, availability of the limiting nutrient will control aquatic biomass growth, algae in particular. Small additions of the limiting nutrient may result in noticeable increases in aquatic biomass production. To have nutrient limitations fluctuate seasonally between nitrogen and phosphorus is not uncommon in some northern prairie lakes. Generally in this region, a combination of high amounts of organic matter in the topsoil and unweathered minerals containing phosphorus contribute to high phosphorus concentrations in water resources. Under these conditions, nitrogen often is the limiting nutrient; however, control of phosphorus inputs may be the most manageable. If phosphorus is chosen for control as a nonlimiting nutrient, improvements to water quality will occur only during an extended period of time.

An important aspect of phosphorus control is related to the release of $PO_4^{-3}$ from lake sediments. This is known as internal nutrient loading. Anoxic or low redox potentials in lake or wetland sediments will contribute to environmental conditions that maintain soluble $PO_4^{-3}$ in the water at relatively high levels. The oxidation state of iron in iron oxides is reduced when the redox potential is lowered. Under these conditions $PO_4^{-3}$ is not readily adsorbed to iron oxide surfaces and is released to solution. Mineralization also continues to release $PO_4^{-3}$ from organic matter. Therefore, aquatic systems that have accumulated a significant layer of eroded sediment likely will not see much reduction in $PO_4^{-3}$ concentrations for extended periods after the implementation of management practices.

## Salts

Salinity, as discussed in previous sections, is an integral characteristic that helps us classify wetlands. Recharge wetlands have naturally low concentrations of salts, whereas discharge wetlands have high concentrations. The type and composition of salts in wetlands and adjacent soils may vary depending on parent material and hydrology. However, under most circumstances, high levels of salinity in the northern prairie pothole region are associated with sulfatic salts. Epsomite ($MgSO_4 \bullet 7H_2O$), mirabilite ($Na_2SO_4 \bullet 10H_2O$) and thenardite ($Na_2SO_4$) are commonly found in salt crusts formed on dry wetland soil surfaces. Deposition of sodium sulfates in some discharge areas in northwestern North Dakota and southern Saskatchewan has been great enough to produce economically extractable quantities. Plants and animals have evolved to flourish under all levels of salinity; therefore, environmental protection or stabilization may require maintenance of rather high concentrations of salts.

Changes in the total salinity and the composition of ions provide an indication of changes in wetland function. Salinity is a good indicator of changes in the wetland environment because of the mobility of soluble ions. Climatic or man-induced changes in hydrology can cause substantial change in salt concentration and composition within relatively short periods of time (from one season to another). Hydrologic differences naturally cause soluble salts to be depleted in some areas and concentrated in others. Therefore, soluble salts are an indicator of hydrologic conditions and can be used as a surrogate to track hydrologic change or trends. Evidence also indicates that changes in the minerologic composition of evaporative salts can be used to gauge long-term trends in salinization. An increased ratio of $Mg^{2+}$:$Ca^{2+}$ has been related to increased salinity in soils with high concentrations of carbonatic salts.

Wetlands serve as sinks for salt deposition both within the wetland and the adjacent edge soils. Wetland edges are active hydrologically due to groundwater flow into and from a shallow water table. Lateral water flow through wetland edges contributes to salt concentration in edge soils. This process contributes to the formation of edge soils with high concentrations of relatively insoluble $CaCO_3$ (e.g., lime). As the groundwater salt load increases in flow-through and discharge wetlands, more soluble salts, such as $CaSO_4 \bullet 2H_2O$ (gypsum), $MgSO_4 \bullet 7H_2O$ and $Na_2SO_4 \bullet 10H_2O$, also concentrate in edge soils (Figure 4). Increased contributions of surface water to wetlands with large concentrations of soluble salts stored in edge soils can contribute to further expansion of salinity into adjacent areas. Evidence of this effect occurs throughout the prairie pothole region where road ditches and lagoons that serve as created wetlands have caused soil salinization of adjacent soils that were nonsaline prior to the man-induced change in hydrology.

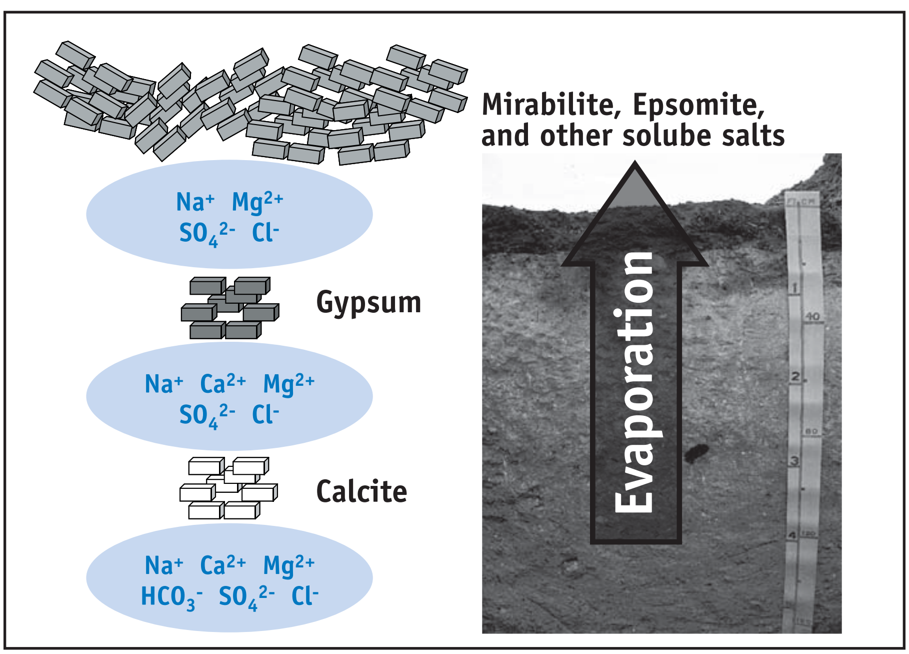



**Figure 4. Salt deposition and soil water evolution in soils on wetland margins**

The salt-sink function of wetlands has important consequences related to wetland drainage. As stated previously, wetlands buffer the aquatic systems. Connection of saline discharge wetlands to streams or lakes with surface drainage ditches will transfer the salt load to these systems. Surface drainage of flow-through wetlands likely will cause increased evapotranspiration and salt concentration from a shallow water table below the drained soil. The reverse process of impounding water, or interrupting surface drainage with dams, also has consequences related to salt concentration. The flow of water through natural surface streams and channels is the mechanism that exports weathered materials, such as salts, from the landscape. Impeding the flushing mechanism of a stream may result in a man-made discharge wetland with increased potential for salinization of impoundment water and edge soils.

## Selenium

Selenium (Se) is an essential trace element for animals, including human beings. Deficiency of selenium in livestock is exhibited when forages have low selenium content due to leached acidic soils. Selenium deficiency is likely to occur if food contains less than 50 parts per billion (ppb). Symptoms of selenium toxicity are known to occur when concentrations in food exceed 3,000 to 5,000 ppb. These levels in food may be reached in forages or grains grown on soils that have high accumulations of selenium (seleniferous).

Selenium is chemically similar to sulfur and occurs naturally along with sulfur (S). When elemental selenium is oxidized, it eventually forms selenic acid ($H_2SeO_4$) comparable to sulfuric acid (H2SO4). The selenate anion ($SeO_4^{2-}$) reacts with a cation to form a soluble salt similar to the sulfate anion ($SO_4^{2-}$). In waterlogged soils, Se and S behave similarly and are reduced to less soluble forms.

Sulfur is present in much larger quantities, but the chemical similarity of selenium allows it to move through the environment in an analogous fashion. Therefore, conditions that allow sulfur to accumulate as sulfatic salts also potentially will allow selenium to accumulate as selenatic salts. Selenium has been found to occur at higher concentrations in discharge wetlands and some drained wetlands where sulfates also were accumulating. Selenium toxicity in wildlife inhabiting some wetlands in the San Joaquin Valley of California has been related to hydrologic changes caused, in part, by irrigated agriculture.

## Mercury and Other Trace Metals

Mercury exists in the environment due to emissions that are both natural and man-induced. Most mercury in the atmosphere is in the elemental vapor form. In water, soil, sediments and organisms, mercury occurs in the form of inorganic salts and organic complexes. Recent estimates indicate that 40 percent to 75 percent of the atmospheric mercury is from combustion of fossil fuels and wastes.

The elemental form of mercury vapor remains in the atmosphere for an average of one year and may be carried for long distances before it is oxidized and deposited. After oxidized mercury is deposited, it is concentrated in water resources through surface flow processes. Once in the soil-water environment, some of the oxidized form of mercury will be complexed in methylmercury compounds, particularly under anoxic conditions. This form of mercury is highly available to fish through the aquatic food web, and accordingly may result in human exposure to high levels of mercury.

Although the mercury cycle is not as well understood as other elements, such as nitrogen, wetlands obviously play an important role in the delivery of mercury to aquatic systems. Oxidation-reduction reactions related to wetness and adsorption-desorption processes related to sediments are influential wetland processes that may release or bind mercury in the wetland environment. Hydrologic change to a wetland, such as drainage, may contribute to increased concentration of mercury in aquatic systems through less volatilization of elemental mercury and increased mobilization of adsorbed mercury through surface runoff.

In North Dakota, mercury concentrations in fish tissue from Devils Lake are elevated. Results of lake sediment analyses from Devils Lake are consistent with atmospheric deposition of mercury concentrated by surface water flow. Although the link has not been proven, extensive drainage of wetlands in the Devils Lake basin may contribute to these elevated levels of mercury.

Other trace metals also have high ratios of man-made to natural levels in the atmosphere and include lead, cadmium, zinc, vanadium, nickel, arsenic and copper. The ratio for mercury actually is relatively low, compared with many of the other trace metals. As described for mercury, the general mechanism of atmospheric deposition and subsequent concentration through surface water flow also applies to these other trace metals. Wetland hydrology may play an important role in determining whether toxic levels of trace metals are reached in various aquatic environments.

Some studies on individual species indicate that reaction to heavy metal contamination is variable among wetland plants. Overall, only limited study has been done on the relationship between these contaminants and the wetland plant community.

## Man-made Organic Chemicals

Organic chemicals produced as a result of man's activities are ubiquitous in the environment. Pesticides, polychlorinated biphenyls (PCBs), dioxins, polycyclic aromatic hydrocarbons (PAHs) and antibiotics are a few of the thousands of organic chemicals that are released regularly through various pathways into the environment. Although the chemistry of each of these compounds is unique, they have the common characteristic of being carbon-based. This means they are subject to microbial attack or degradation and they are attracted to organic matter in soils and sediments.

The attraction of these chemicals to organic matter allows them to follow the movement of water-transported soil sediments. They may be adsorbed and degraded in the soils that they contact, or they may be transported to other locations with eroded sediment. Transported sediment with its load of adsorbed chemicals often is deposited in wetland systems. The fact that many pesticides and other man-made organic chemicals are degraded in wetland environments is well-documented. In this case, healthy, functioning wetlands serve as environmental filters and protect aquatic systems. However, if the rates of addition exceed the capacity of the wetland to perform chemical transformations, toxic concentrations may result. The consequences may be twofold: 1) deterioration of the wetland biotic system, causing a reduction in function; and 2) elevated chemical concentrations in adjacent aquatic systems due to reduced wetland function. Herbicides used in and around wetlands to control weeds in row-crop situations can decrease production and species richness of wetland plant species. In certain instances, a whole wetland plant community can be eliminated by herbicides, such as when used to control weeds on summer-fallowed land.

As noted with other potential water contaminants, the role of wetlands as an environmental filter is closely connected to the maintenance of natural hydrologic conditions. The balance between sink and source changes with major shifts in hydrology, either natural or man-induced. Generally, losses of surface water impoundment and lowered water tables will result in reduced capacity of wetlands to attenuate and transform man-made organic chemicals.

# Modifications to Wetland Systems

## Drainage

Permanently removing water from the soil surface and lowering the water table changes the hydrologic regime to one more favorable to development and agricultural production. Saturated and/or inundated soils make the operation of most equipment cost prohibitive and cannot physically support structures. The lack of oxygen, cool soil temperatures and physical challenges of working saturated soils make crop production unlikely except for a few exceptions, such as rice and cranberries.

Drainage of hydric (wet) soils, either by surface or subsurface (tile) drains, not only removes water, but also changes the soil environment from anaerobic to aerobic conditions (Figure 5). A practical benefit of the change is increased mineralization of stored soil organic matter and release of nutrients for crop production. Changing to aerobic conditions has been observed to have detrimental effects, such as lowered pH caused by oxidation of iron pyrite; however, this is not a likely scenario in the calcareous tills in the NPPR. More likely, the processes of increased mineral precipitation and adsorption of soluble phosphorous might contribute to plant deficiency.

Introduction of an aerobic environment to a wetland soil, combined with steady removal of surface water, shifts the carbon and nutrient equilibrium. The wetland becomes a source for the release of carbon dioxide ($CO_2$), nitrate ($NO_3$) and phosphate ($PO_4$). The wetland loses its capacity to remove nitrate through denitrification; therefore, the increased nitrate produced by mineralization has higher potential to be translocated with drainage water. The loss of the capacity to impound water due to more efficient water removal, coupled with greater availability of nutrients, increases the potential for delivery of nutrients to aquatic systems downstream.

## Sediment Trapping

Concave slopes often occupied by wetlands serve as sediment traps on the landscape. The wetland serves as a filter for adjacent aquatic systems. When surface drainage connects basins, the upper wetland basins lose some of their sediment-trapping capacity. On landscapes where erosion has been accelerated substantially, drainage actually may reduce excessive deposition in the wetland and improve wetland function. However, the problem of sedimentation is passed downstream, eventually impacting aquatic systems.

Sediment impacts to aquatic systems go far beyond the physical problems related to turbid water and muddy bottoms. Wetlands have evolved to transform the soluble

- Hydric conditions in wetland soil consist of long periods of complete saturation of pores to the soil surface causing anaerobic conditions throughout
- Organic matter builds up, methane and nitrous oxide gas is released, iron is mobilized, selenium is demobilized
- Wetland drainage aerates the soil profile with oxygen and reverses these processes

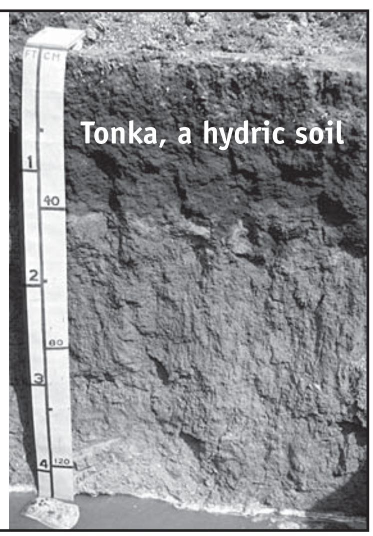



**Figure 5. Drainage changes the aeration and chemistry of hydric soils**

and adsorbed chemical load delivered in surface runoff into nontoxic forms that allow diverse biotic conditions to flourish. When wetlands are removed from the landscape, soluble and adsorbed chemicals are delivered directly to aquatic systems. Streams, rivers and lakes have not evolved the capacity to withstand increased chemical inputs, particularly at the rates delivered due to accelerated erosion. The result is hypereutrophic conditions and chemical toxicity that reduces the biotic diversity and value of aquatic water resources.

Sedimentation in wetlands is a natural process on native prairie but is greatly increased by soil erosion from cultivated catchment basins. The type of crop planted directly influences the amount of sedimentation. Row crops will deliver more sediment than small-grain crops. Not only does increased sedimentation occur, but also more turbidity, greater amount of surface water entering the wetland and the overall "life span" of the wetland could be affected.

Sedimentation and turbidity affect species composition, species richness, biomass and cover ratio of wetlands. Submersed species are most affected by sedimentation and turbidity in a wetland. Sedimentation reduces the germination and over-winter survival of Eurasian watermilfoil and water celery. Increased sedimentation decreases the amount and depth of water held within a wetland, and water is not maintained during the entire growing season. Sedimentation and lower water levels could cause upland species to encroach on smaller wetlands and overrun the wet meadow zone. Decreased water depth may contribute to decreased species richness by allowing certain plants, such as cattails, to dominate the wetland plant community.

Nutrients often accompany sediment in the runoff of cultivated wetland catchment basins. One of the most frequent effects of an increased nutrient load on wetland plant species is an increase in the biomass and cover of emergent and floating plants. Floating species, such as duckweed, also increase, but submersed plant species decrease. High nutrient loads seem to eradicate Eurasian watermilfoil and hornwort, but algae will bloom under these conditions. Moderate nutrient loads do not appear to affect hornwort and bladderwort, even though the diversity and productivity are diminished. Overall, severe nutrient loads will cause more drastic changes in the vegetation, including loss of species, a change in the total plant community and changes in individual species.

## Reduced Soil Quality in Wetland Catchment Soils

Land use in the upslope areas adjacent to wetland basins may have considerable influence on wetland hydrology. Runoff from the upslope soils will occur when the rainfall rate surpasses the infiltration rate for a specific event. Soil properties such as texture and structure control the amount and type of pores that conduct water through the soil profile. Soil texture is determined by the percentage of sand, silt and clay, and is a relatively permanent soil property. On the other hand, soil structure is determined by how the primary particles of sand, silt and clay are aggregated, and is subject to substantial change during relatively short periods of time. Soil organic matter plays a major role in determining the stability of soil aggregates. Land use practices that affect soil organic matter also affect soil aggregation, porosity and water infiltration.

Soil pores range in size and distribution. Larger pores that allow water to drain by gravity are greater than 30 microns in diameter and often referred to as macropores. Macropores that connect with the surface have substantial influence on infiltration. These pores exist due to the stacking of the larger soil aggregates. The larger soil aggregates are stabilized or bonded by organic materials that have the least resistance to deterioration, such as living biological tissue (e.g., root hairs) and polysaccharides (sugars). Consequently, cultivation causes a relatively rapid loss of large soil aggregates and macroporosity. Water infiltration rates are reduced, causing increased runoff, erosion and deposition of sediments and adsorbed chemicals in concave hillslope positions that wetlands often occupy.

Deterioration of physical properties of surrounding soils can cause observable hydrologic change to wetlands even though drainage has not been attempted. Increased runoff during rainfall will contribute to high pond levels, but decreased subsurface flow will allow pond levels to drop at a more rapid rate. The result is greater instability created by wider, more rapid fluctuations of pond levels. Wide fluctuation of water input to wetlands introduces longer periods of low water tables and aerobic conditions. Increased mineralization and release of soluble nutrients is one result. Decreased denitrification may be another result. Release of other soluble phases of chemicals such as selenium also may follow.

Another consequence of hydrologic change in wetlands induced by upslope land use is redistribution of shallow salts. The perimeter of a wetland is a zone of active water movement that allows concentration of a variety of salts.

The distribution and location of the different types of salts is influenced by their solubility. Calcium carbonate, commonly referred to as lime, is a salt with low solubility that is concentrated during long periods of time in soils on the edge of almost all wetlands. More soluble salts, such as sodium and magnesium sulfate, also often are concentrated in soils on wetland edges, but are subject to relatively rapid translocation created by short-term changes in hydrology.

Evaporation from the wetland edge is a mechanism that pulls salts from the wetland upslope into the adjacent soils. Movement of water down-slope due to subsurface flow is a mechanism that moves salts away the adjacent soils back toward the wetland. When land use increases surface runoff at the expense of subsurface flow, the balance of soluble salt movement is shifted in a lateral direction outward from the wetland. Encroachment of soluble salts into adjacent upslope soils causes a shift in the wetland plant community to species more resistant to high osmostic pressure. It also reduces the productivity of crops grown on adjacent soils for the same reason. Longer periods of low pond levels also will result in higher pond salinity due to the concentration of salts as pond water is evaporated.

Increased fluctuation in pond levels also will alter the balance between groundwater recharge and discharge. Long periods of dry conditions will not only lower water tables, but also can cause a wetland to change from a flow-through or discharge condition to a recharge condition. Aerobic conditions during the dry period will mobilize nutrients and other chemicals, whereby a sudden influx of runoff into the wetland basin may push them into the groundwater below.

Note that large fluctuations in wetland pond levels also are associated with climatic variation. In the NPPR, water in wetland ponds has risen to unprecedented levels in the last 20 years. Clearly the local hydrologic conditions surrounding most wetlands have changed in a relatively short period of time. This type of natural climatic fluctuation is consistent with the continental climate of the region. Natural fluctuations in water, sediment and chemical wetland budgets result in changes to wetland plant communities, water quality and adjacent soils. When addressing management issues related to water level fluctuations and land use, the relationship to climatic variation also must be considered.

# Assessment of Wetland Function and Biotic Integrity

Assessment of function provides an estimate of the capacity of a wetland to participate in a given environmental process. Wetland function often is divided into three major categories: 1) hydrologic; 2) biogeochemical; 3) habitat and food web support. Function should not be confused with value, which is an estimate of worth to society.

## Hydrogeomorphic Model (HGM)

The three major categories of wetland function listed above have many specific functions within them. There is a large amount of variability among individual wetlands to perform each of these specific functions. The first step of wetland assessment methods, such as the hydrogeomorphic (HGM) model developed by the Natural Resource Conservation Service and U.S. Army Corp of Engineers, is a classification of wetlands established on hydrogeomorphic factors such as geomorphology, water source and transport, hydrodynamics, water chemistry and soil properties. Basically, wetlands are standardized in groups based on similar abilities to perform natural functions. Within these groups, reference wetlands that represent relatively undisturbed conditions are used to set the specific criteria for assessment of functionality (Figure 6). The algorithm containing the criteria developed for each wetland group is referred to as a hydrogeomorphic model. A regionalized "reference system" is created by sampling and comparing functionality of a number of unimpaired and impaired wetlands within a class. The level of function performed by a given wetland is determined by comparing it to the unimpaired reference conditions. A hydrogeomorphic model for temporary and seasonal wetlands in the NPPR has been developed.

## Index of Plant Community Integrity (IPCI)

The integrity of the native biological components of a wetland is known to be a reflection of the condition or health of a wetland. For example, plant species have different ranges of tolerance to a variety of environmental factors, such as inundation, wetness, salinity, pH, sedimentation, physical alterations, etc. When wetland

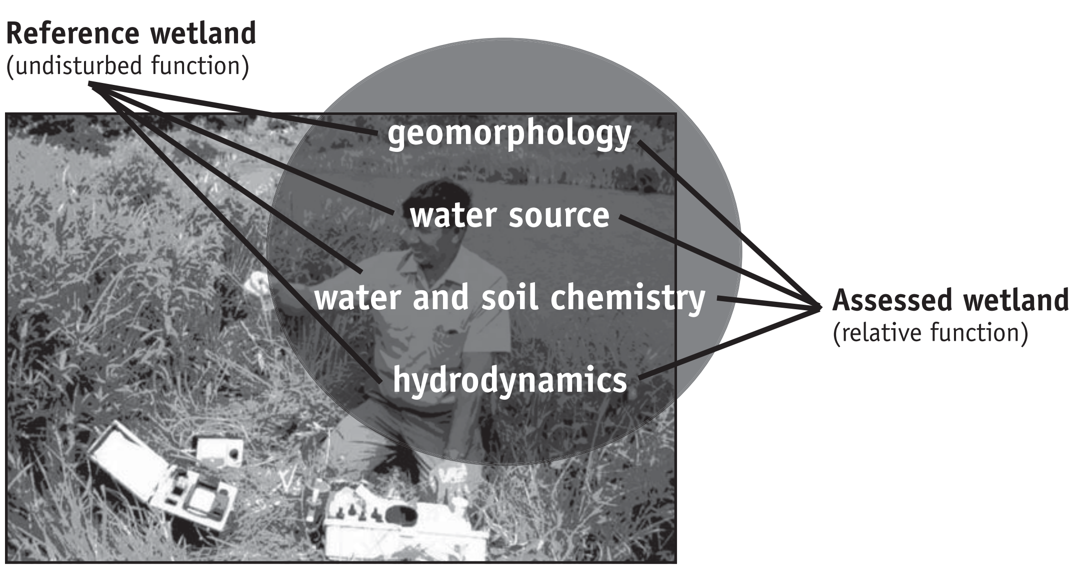



**Figure 6. Assessment with the hydrogeomorphic model compares measured values of function in undisturbed wetlands to disturbed wetlands of similar class**

conditions are disturbed, one of the first indicators of reduced condition or health is a change in the wetland plant community. As the intensity of disturbance increases, the native perennial plant species' richness and diversity decrease in number and cover, and annual, biennial and exotic species will increase. In many cases under intensive disturbance, such as cultivation, the native plant community is totally decimated and weedy annuals or mono-cultural stands of invasive exotics will dominate.

An index of plant community integrity (IPCI) has been developed for temporary, seasonal and semipermanent wetlands for the majority of the NPPR. Similar to the HGM model, the IPCI was developed to assess wetlands across a range of disturbance. Plant community attributes (e.g., native perennial species richness; percent of annual, biennial and introduced species, etc.) are quantified and compared to the level of disturbance in upland catchments that range from well-managed rangeland to intensively cultivated cropland. The relationships determined allow plant community attributes to be used to predict disturbance intensity and/or wetland condition. A value of wetland condition can be assigned by locating its position on the disturbance gradient (e.g., low [native prairie] high [cultivation]). Five categories of wetland condition are recognized and range from very good to very poor.

Note that extrapolation of wetland assessment methods beyond the experimental conditions or region of data evaluation is risky and not recommended.

# Soil Management and Wetland Restoration

The degree of wetness controls wetland soil properties, which in turn controls the biotic community or habitat. The balance between aerobic and anaerobic conditions is critical to wetland function. This is a hydrological problem that needs to consider periods and depth of wetland inundation. Hydrologic conditions in the wetland depend on surface and subsurface flow to and from adjacent areas. Wetland restoration and protection must account for the hydrologic connection with soils in the adjacent areas that are not wet but transmit water.

Restoration of previous hydrologic conditions depends not only on reintroducing impounded water, but also on return to the previous balance between inputs from surface and subsurface flow. This requires changes in management to upslope areas adjacent to the wetland. In this case, management techniques that provide increased carbon sequestration need to be applied to improve the structural stability and porosity of upslope soils (Figure 7). Increased infiltration comparable to well-managed rangeland on similar soils is the goal.

Management of upslope soils that are cropped will be more challenging than range or pasture. The impact of cropland management to wetlands is highly variable, depending on a host of different factors. However, some general practices can be discussed in terms of their influence on wetland systems. Management effects may be categorized into tillage, rotations, conservation practices and structures, chemical inputs and water inputs.

## Tillage

As discussed previously, tillage has profound effects on soil aggregate stability and size, which causes a reduction in water infiltration. The impacts from tillage can be minimized by using implements that expose the soil for relatively short periods and leave relatively high amounts of plant residue on the surface. Moldboard plowing, disking and black summer fallow are practices that cause extreme stress to soil aggregates. Reduced-tillage practices will promote less mechanical stress from implements, rain and wind on soil aggregates. At the same time, increased return of plant residues and decreased mineralization will promote higher levels of the types of organic matter responsible for stabilizing the larger soil aggregates.

Some of the challenges of reduced tillage are related to decreased soil temperatures and higher amounts of soil moisture that are desirable during germination and seedling growth. Increased application of nutrients may be required

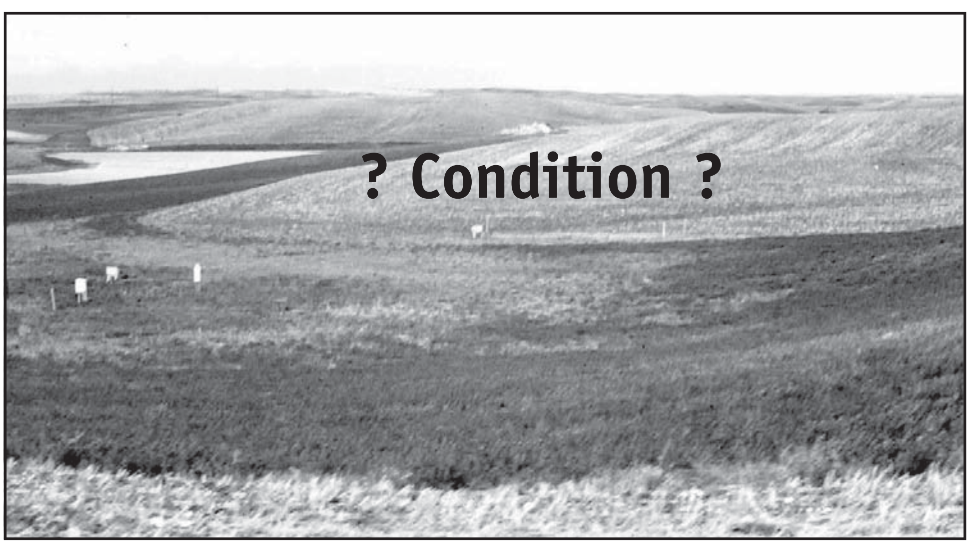



**Figure 7. Wetland condition depends on basin water management and upland land use**

early in the growing cycle. Greater amounts of available nutrients in the surface soil can lead to higher losses to both surface and groundwater systems. Increased levels of weed and disease infestations may require greater use of pesticides and have consequent impacts on water resources.

## Crop Rotations

The period of soil exposure to the elements has a strong influence on the amount of stress placed on soil aggregates. The crop canopy and plant residues left after harvest protect the soil surface from the impact of rain, water and wind shear. The rotation that provides the least amount of protection is clean summer fallow during the most erosive periods of the year. Row crops generally take longer to develop a protective canopy, compared with small grains or other crops grown without discernable rows. The inter-row area has the potential to focus surface runoff, causing increased shear stress and erosion.

Some crops, such as wheat and barley, are more effective in utilizing applied nutrients, compared with corn or potatoes. Other crops, such as alfalfa, are more effective in extracting water and nutrients from deeper parts of the soil profile. Rotations that include deep-rooted crops help scavenge nutrients and water left by less efficient crops. Finally, crop rotation almost always increases crop yield, compared with continuous cropping systems. This is probably related to number of things that improve plant health, such as breaking disease cycles. Vigorous plant growth provides greater soil protection through soil canopy development and plant residues.

## Conservation Practices and Structures

Removal and transport of sediments is a geologic process that controls the formation of landforms. The geologic rate of landscape formation is relatively slow. However, under extreme conditions that either increase the erosive forces or reduce the ability of the soil surface to withstand those forces, erosion rates may be accelerated substantially. A study of erosion rates in Iowa showed increases of seven to 900 times after settlement. Conservation practices and structures will not eliminate the natural processes of sediment removal and deposition important to landscape formation, but if applied correctly will reduce the rate of erosion to one closer to the natural level.

Farming practices such as contour tillage and planting, strip cropping, shelterbelts and grassed waterways are designed to reduce the potential for detachment and movement of sediment. Farming across, rather than down, hill slopes reduces the potential for runoff to focus into rills and small channels where high-shear stress develops. Using strips of crops, such as beans and alfalfa, in the same field allows detached soil particles from the less protected soil (beans) to be trapped in the protected crop strip (alfalfa). This practice works to reduce off-site soil movement by both wind and water. Drainageways are stabilized to allow the transport of water through the landscape without gully development. Shelterbelts of trees and shrubs are used to break the velocity of the wind and reduce wind shear.

Weather extremes often overwhelm conservation practices and more robust measures are required to protect soil and water resources. Terraces, water diversions and water impoundments require substantial effort to construct and maintain. In some places, these structures are highly effective in protecting water resources by providing sediment trapping and controlled transport of runoff through the landscape.

## Chemical Inputs

Controlled input of nutrients and pesticides is extremely important to plant health and, subsequently, soil and water protection. Appropriate nutrient and pesticide application depends on knowledge of the plant environment. The goal is to apply enough nutrition to the plant so it meets its genetic potential for yield without leaving excessive residual amounts of nutrients in the soil. Efficient use of nutrients requires soil testing and sometimes plant analyses of nutrient status. Useful soil testing requires implementation of a well-designed sampling plan. Nitrogen status needs to be determined most regularly, compared with less mobile nutrients such as phosphorus. Nitrogen testing may be required every year under a highly intensive cropping rotation.

Pest monitoring or field scouting should be used to predict when levels of infestation will have an economic impact worth treating. A comprehensive management plan that includes all the options available for pest control, including application of pesticides, should be developed. Integrated pest management systems have been shown to economically control pests and also reduce the overall use of pesticides.

## Water Inputs

Water often is the most limiting nutrient with respect to plant growth. The benefit of increased available water in the soil profile usually contributes to improved plant growth and yields. As discussed previously, this leads to increased levels of plant residue that helps promote protection from the erosive forces of wind and water. Greater soil protection effectively provides more efficient use of water inputs in many upland soils.

Not all upland soils, however, exhibit the same positive influence of practices that promote increased levels of soil moisture. Too much of a good thing can be detrimental to plant growth for a variety of reasons, such as reduced soil temperatures and low levels of oxygen. Evidence indicates that timely removal of water from these soils either by surface or subsurface drainage systems will improve plant growth and increase soil protection through greater plant residues. Also, soil drainage will increase water infiltration, thus reducing the potential for runoff and water erosion. However, drainage allows low-intensity land use with permanent plant communities to be replaced with higher-intensity land use with intermittent vegetation. The result may be quite successful from an economic point of view, but the potential for soil erosion also will increase. For example, the wet soils in the Red River Valley are highly productive due to surface drainage, but eroded sediment generated from these soils, particularly by wind, continues to challenge resource managers.

Water input management is critical on irrigated soils for both economic and environmental reasons. Application of water in excess of plant needs may contribute to water table buildup, nutrient and salt leaching to aquifer resources, and increased runoff and erosion due to surface soil saturation. Water applications that don't meet the crop-growth requirements will result in lower yields, less plant residues and decreased protection of the soil surface from wind and water.

Before attempting irrigation, the compatibility of the soil to water application should be estimated. Soil properties such as slope, texture, internal drainage and salts are considered with respect to the salinity and sodicity of the irrigation water. Irrigation of soil with incompatible water can lead to substantial loss of soil productivity due to salinization, sodification, erosion and water table buildup. The damage to the soil resource will extend to deterioration of surface and groundwater resources.

After determining soil and water compatibility, the single most useful recommendation is adaptation of an accepted water scheduling method to the grower's management system. The "checkbook method" is popular in the northern Great Plains and accounts for available soil water and crop water use. Matching crop water requirements with water inputs is the ultimate goal. If this can be accomplished, crops can be produced with the least amount of impact to soil and water resources.

## Grazing Systems

Many wetlands in the NPPR are found adjacent to rangeland or pastureland, as opposed to cultivated crops. In these areas, grazing animal management influences soil condition and resultant impacts to wetlands. Grazing of prairie grasses stimulates root growth and plays a key role in prairie soil development. The salient feature of a prairie soil is a thick topsoil with a high amount of organic matter and stable aggregates.

Although the productive qualities of prairie soils can be linked to grazing animals, there is a limit. Studies show that many factors, such as soil type, slope, aspect, plant type and range condition, will affect runoff and erosion from prairie soils. However, the most important factor is grazing intensity. When prairie grasses are grazed so intensely that the plant cannot recover nutrient reserves lost during early grazing, the plant cover and root mass diminish. The result is reduced infiltration of water and increased runoff that contributes to sedimentation and hydrologic changes to wetlands.

Some impacts also are related directly to grazing of wetland plants. Wetlands subjected to grazing contrast in dominant plant species, compared with wetlands with other land uses, such as haying, cultivation or idle conditions. Depending on its intensity, grazing can increase species diversity and diversity along environmental gradients, as well as increase wetland plant community boundary definition. Grazing decreases dead plant matter, and overgrazing can lead to decreased primary production. Overgrazing and severe trampling will reduce plant cover and increase the amount of bare soil. The effects of livestock trampling occur mainly in the exterior zones of a wetland. Many wetland plant species are adapted to grazing, or can withstand the grazing pressures. Overall, the effects of grazing on wetland plant community composition, species richness and cover can vary greatly with grazing intensity. Because grazing historically has been a disturbance within the prairie wetland region, wetlands located on well-managed rangeland should exhibit high-quality conditions.

Stocking rate management is critical to maintenance of good range and soil condition. Generally, stocking rates never should exceed levels that allow the plant cover to diminish below 30 percent. This usually can be achieved with grazing management that utilizes 50 percent to 60 percent by weight of the above-ground biomass. A rule of thumb often applied to grazing systems is "take half – leave half." Utilization charts for different grass species have been developed for range managers to gauge biomass removal with grazed plant height.

Timing of grazing also is an important element in maintaining range and soil resources. Grasses are most vulnerable to stress in the early part of their growth cycle. Usually grazing of native rangeland is not recommended prior to May 20 in southeast North Dakota and June 1 in the rest of the state. Pastures with introduced cool-season grasses, such as crested wheatgrass and smooth bromegrass, can be used to extend grazing into April and May. Pastures with introduced warm-season grasses, such as Altai and Russian wildrye, can be used to extend grazing into the fall.

Rotation grazing and range improvement methods help maintain economic stocking rates without causing deterioration of plant and soil resources. Range improvements, such as fencing, water development, burning, mowing and mineral placement, help provide a more even distribution of animals. Water development also helps place watering sites upslope from depressional areas with wetlands. This reduces damage to wet soils and also diminishes the consumption of stagnant water, a threat to animal health. Other techniques, such as weed control, fertilization, seeding and interseeding, and runoff entrapment, help improve plant health and range condition.

# Wetland Basin Management

## Mowing

Mowing or haying is another common practice influencing NPPR wetlands. The plant material removed is used as forage or bedding for livestock. Mowing also occurs around urban wetlands, usually for aesthetic or management values. Haying usually occurs in situations where the upland has been planted into an alfalfa or grass alfalfa mixture. Haying wetlands is common where the uplands have been cultivated but the wetland area is too wet to be cultivated. The most commonly hayed areas of a wetland are the wet meadow and shallow marsh zones. These zones, especially the wet meadow zone, usually are accessible to farm machinery in the fall. Wetland researchers believe that extensive haying over time will increase specific types of plant species, such as white top. Also, livestock owners often introduce a species, such as reed canarygrass, into wetlands as a desirable hay species. Mowing or haying can, therefore, affect the composition of wetland plant communities through long-term haying or by physically planting a desirable forage species.

## Cultivation

One of the most severe types of disturbance affecting NPPR wetland vegetation is cultivation. Principally, temporary and seasonal wetlands or the temporary and seasonal zones of larger wetlands are cultivated. Cultivation favors weedy, often introduced, annual and perennial species, and eradicates native perennial vegetation. Invader species establish quickly after water levels fall. Stewart and Kantrud (1971) provide a list of common species found in cultivated wetlands in their “cropland drawdown phase” and “cropland tillage phase.” The “cropland drawdown phase” consists of drawdown annual species that usually are found on open, muddy areas of wetlands. The “cropland tillage phase” consists of weedy annuals and row crop or small-grain species that can be planted because of drier conditions. Cultivation also establishes a unique uneven microtopography where upland weedy annuals, drawdown plant species and naturally occurring wetland species exist close to one another. Cultivated wetlands will differ in plant species assemblages from native situations.

## Restored Wetlands

Many NPPR wetlands have been restored with backing from federal, state and private organizations. Most of these have been restored through the Conservation Reserve Program. Recently restored wetlands have fewer species than those found in natural conditions. Compared with natural wetlands, restored wetlands often have different species associations, distribution and abundance of species according to elevation, and number of species and total number of seeds in the seed bank. Also certain species, such as reed canarygrass and rice cutgrass, may invade rapidly and inhibit the establishment of desirable species.

## Idled Wetlands

Wetlands in the NPPR sometimes are left idle as a part of the Conservation Reserve Program, waterfowl production areas, national refuges, state game management areas or privately owned land. Idled wetlands often create opportunities for invasion of cattails, willows and cottonwoods, particularly in areas that once were under cultivation. Idling salt-marsh wetlands decrease species richness and vegetation types. Common reed has been observed to increase in wetlands left idle.

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