Livestock management and water quality

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Prepared for:

Central Coast Rangeland Coalition

-in partnership with-

Midpeninsula Regional Open Space District

March 15, 2011

Introduction

Much of California's water supply cycles through the 16 million acres (6.4 million hectares) of annual rangeland in the state (George et al. 2004). These 16 million acres make up a large proportion of the state's total land area, which means that many of our water taps, wells, and irrigation canals serve up water that either fell on rangeland or flowed in streams fed at least in part by rangeland watersheds. The functioning of rangeland as watershed land is therefore a topic of great concern. If in its journey through rangeland, water acquires a large sediment load, excessive levels of nutrients, or potentially harmful organisms, its value as drinking water—and possibly as water for wildlife, aquatic life, agricultural production, and livestock—can be adversely affected. Moreover, because water travels long distances in California, both naturally and in human-engineered transfers, the pollution of water in one local area can have far-reaching consequences elsewhere, affecting distant human consumers, regional fisheries, threatened or endangered aquatic species, and ultimately the state's marine environments.

The functioning of rangeland as watershed land—its ability to yield water of adequate quality—is determined largely by how its resident livestock are managed. Livestock (mainly, in the Central Coast region, herds of beef cattle, but also dairy cattle, sheep, goats, horses, and a few other types of large ranging animals) exist on these lands primarily as components of agricultural production systems, but as living organisms they also have important effects on other resources, including vegetation, soil, and water.

In this paper I broadly review the published scientific literature on interactions between livestock management actions and water quality. The goal is to provide information that can be used to develop management strategies designed to protect and enhance the function of Central

Coast rangeland as watershed land, protecting water quality without compromising the diverse uses to which we put these multifunctional working landscapes.

Water quality can be evaluated based on a variety of biotic, chemical, and physical parameters depending on the context and goals of evaluation. In this review I focus on three elements of water quality directly affected by the presence of livestock: (1) sediment load—the amount of particulate matter contained in the watercourse, both settled and in suspension; (2) nutrient levels, with particular emphasis on nitrogen and phosphorous; and (3) the presence of parasitic, pathogenic, and eutrophying organisms, the latter in response to excessive levels of the nutrients in the second category.

Before reviewing the literature that sheds some light on the relationships between livestock, livestock management, and these elements of water quality, I outline some of the basic ecological concepts that are relevant to understanding and putting in context the findings and conclusions discussed in this review. After discussing the literature as it relates to each of the three categories of water quality, I discuss some of the management actions that can be used to modify interactions between livestock and water quality. While the primary goal is to provide information most relevant to livestock management and water quality in the Central Coast rangelands of California, the review integrates findings from studies of a variety of related systems. There are two appendices at the end of this document. The first is a summary of key research findings relevant to management of specific water quality issues on rangelands. The second is a glossary of key terms defined as they are used in this paper.

Background

One of the challenges of watershed management is that lands within any given watershed are typically managed for multiple stakeholders who as a whole have a wide variety of often conflicting goals. Understanding when and why these goals are compatible and when and why they are not is an important part of meeting the interests of multiple stakeholders. This process requires a basic understanding of ecosystem functions within watersheds and the ways that management actions interact with those ecological processes. Though ranchers and public land managers have no designation as such, they are in fact some of the primary stewards of our regional water resources; therefore it behooves all acting parties to seek collaboration informed by an understanding of each other's needs and goals and by the best available science.

Watersheds and Hydrologic Function

Hydrologic function, the ability of a watershed to regulate seasonal flows and purify water, is among the most crucial of ecosystem services. In any watershed, the properties related to hydrologic function are influenced by a wide range of biotic and abiotic features that are themselves influenced by human resource use. The capacity of a watershed to buffer large fluctuations in surface flows and to filter water is largely governed by the land's soil and vegetative cover and by complex interactions between plants and soil. Plants physically absorb the energy of rainfall and impede surface flows, allowing greater opportunity for infiltration of water into the soil during high-volume events (Morgan et. al. 1997). At small spatial scales this impedance helps prevent erosion of soils and sedimentation of waterways, while at larger spatial scales it moderates surface flows following large rain or snow-melt events.

Soil affects hydrologic function in a variety of ways, as determined by its physical, chemical, and biotic properties (Mills et al. 2006). The physical structure of soil and its organic content can affect several important interactions between soil and water: how surface flows penetrate the soil and move into the ground water, the length of time water is resident in the biologically active parts of the soil profile (Tate et al. 2004), and the ability of the soil to trap particles or dissolved contaminants moving vertically or laterally through it. Both plant roots and the soil microbial community are capable of taking up dissolved compounds in runoff and provide further purification of water as it moves through watersheds (Chandra & Yadav 2010, Shilling & Jacobson 2009, O'Farrell et al. 2009).

Several studies have documented and quantified the contribution of watershed properties such as vegetative cover and soil structure to the capture and purification of water. In a study of restored prairies, Schilling and Jacobson (2009) found that every year after restoration, the groundwater under the restored sites had its concentration of two water contaminants reduced—by an average of 0.58 mg/l per year for nitrate and an average of 0.52 mg/l per year for chloride. O'Farrell et al. (2009) demonstrate that intact *renostroveldt,* a grassy scrubland of South Africa, reduces runoff and provides better infiltration than land converted to other uses. These and other studies confirm that it is largely through interactions between plants and soil that watersheds provide the services of regulating flow and purifying water.

The importance of hydrologic function to human well-being is readily apparent in a variety of examples from around the world. The city of Bogota, Columbia, with a population of more than 8 million, secures most of its water from vast pristine wetlands in the Andes. This ecosystem consistently delivers water at 28 m^3 per second with little need for treatment (Postel &Thompson 2005). In the U.S., several municipalities have avoided costly expenditures for preconsumer water treatment facilities by investing in watershed protection. For example, the city of New York spent $1.5 billion on watershed protection over a period of ten years to avoid spending $6 billion on the creation of a municipal filtration system and an estimated $3 million annually in operation costs (Blain et al. 2006). A survey of 27 US water supply systems by Ernst (2004) clearly showed that those with the highest percentage of watershed comprised of intact forests (as opposed to cultivated and urbanized land cover) had substantially lower water treatment costs per unit of treated water.

We are all stakeholders in the health and use of water resources. The movement of water into, through, and out of watersheds connects diverse stakeholders in profound ways. The same water that is the source for municipal drinking water supplies provides many ecosystem services as it moves through the watershed. On its course, water may pass through rangelands where it supports forage growth and provides drinking sources for livestock, and it collects in surface streams and ponds that support a wide variety of wildlife (including numerous special status species). It percolates into groundwater basins that may be the source of water for individual or municipal wells, and ultimately returns to the ocean. Thus, actions in even the farthest reaches of our watersheds can affect many of the other uses.

Ecological Roles of Livestock

To constructively consider the ways in which livestock interact with our watersheds, it is useful to characterize these animals as organisms in dynamic ecosystems. All livestock on rangelands have a niche, or ecological role, that can be described as the way in which they interact with the environment while meeting their needs as living organisms. The ecological role of livestock varies among species and is influenced by the livestock management regime, but it is defined most essentially by the ways in which these animals preferentially use their habitat to find clean water, adequate nutritious food, an appropriate temperature regime, and resting places (George et al. 2007). In seeking to fulfill these needs and comforts these animals influence the landscapes and ecosystems in which they exist.

Livestock are important primary consumers, capable of contributing to both short-term and long-term removal of biomass and nutrients from the systems in which they forage. Some of the matter consumed by livestock is redistributed as solid, liquid, or gaseous waste and thus returned to the systems, but if rates of nutrient deposition exceed the capacity of vegetation and soils to recapture them, then these nutrients may be lost through transport in runoff or gaseous emissions. Because most livestock are ultimately transported out of the rangelands through harvest, the nutrients that went into the making of their muscle, bone, skin, and organs—or, in the case of dairy cows, their milk—are removed from the systems in which they fed. Thus livestock may increase nutrient availability in the short term through deposition of wastes but cause long-term nutrient export through harvest.

In addition to affecting nutrient cycling and transport, removal of biomass by primary consumers changes the structure of plant communities. The influence of large herbivores is important in structuring vegetation and maintaining diversity in grasslands around the world (Gibson 2009). In terms of the physical structure of vegetation, intense livestock foraging can lead to shorter-statured vegetation during grazed periods. This may be expressed by potentially taller species being maintained at a lower height or by the creation of conditions that favor shorter-statured species (Hayes & Holl 2003, Suzuki 2008). Different classes of livestock tend to have different degrees of selectivity in their foraging habits and may therefore influence plant community composition in different ways. For example, if the kind of livestock using a particular site have a preference for grasses over forbs, then communities exposed in the long term to these animals may become dominated by forbs as their growth is relatively un-interrupted by the selective herbivory (Evja et al. 2009). There has been debate about this subject, however. There is evidence that in semi-arid rangeland, such as is found in central California, grazing intensity and site conditions may be more important factors than the selective preferences of livestock in structuring vegetation (Bartolome 1993, Bartolome & McClaren 1992).

In addition to their influence as consumers, livestock may contribute to physical disturbance that shapes the environments in which they exist. Over time groups of large animals may compact soils, particularly in areas of high use. This change in soil bulk density (SBD) may affect hydrology and nutrient dynamics. In a study on cattle grazing and SBD in the central Sierra foothills, Tate et al. (2004) found that sites with higher-intensity grazing treatments had higher bulk soil density (greater compaction). Their study included sites with no grazing for more than 26 years, sites with no grazing for 6 years, and sites grazed at low, medium, and high intensity (grazing intensity was determined by residual dry matter, or RDM; the levels were 1100 kg/ha RDM, 670–900 kg/ha RDM, and less than 470 kg/ha RDM, respectively). There was no difference between the two categories of grazing exclusion but both had significantly lower SBD than any of the grazed treatments. Among the grazed sites, those grazed at the lowest intensity (1100 kg/ha RDM) had significantly lower BSD than the medium- or high-intensity grazed sites, which were indistinguishable from one another. Soil bulk density is important in watershed function because low BSD is positively correlated with high soil porosity and good water infiltration (Tate et al. 2004).

Managers and stakeholders in watershed stewardship have a range of values associated with livestock and rangelands, but sound decision-making requires that we consider the variety of ways these animals may interact with their environment prior to our assignment of value. Once livestock are introduced to a landscape, they are part of a dynamic system that responds to their influence in multiple ways: the structure and composition of the vegetative shifts, microbial populations increase or decline, and the structure of the soil changes. Whether these changes can be considered good or bad is in part dependent on the manager's or stakeholder's goals, but an understanding of their significance for hydrological and ecological function provides the foundation for judging their relative desirability in a larger context.

Livestock Operations

Management of livestock in California's central coast is diverse and is driven by a wide array of managers and stakeholders who may work independently or in cooperation to meet their respective goals. Livestock operators own and lease varying proportions of the lands they use. Some may focus on cow-calf operations while others may focus on stocking operations. Within these general categories, mangers operate at different scales. In the case of public lands, managers typically don't own animals but may call on livestock operators to help meet other resource goals with use of livestock. Rangelands in this region are a mosaic of private and public holdings of widely varying sizes, continuity, and suitability for sustaining different classes of livestock. All livestock need adequate water, food, and space. How these needs are met depends on the goals and resources available to the manager.

Effects of Livestock on Water Quality

Erosion and Sedimentation

As water moves across terrestrial surfaces, soil particles of various sizes and textures may be suspended and carried into water bodies, where they affect water quality in ways that are important to people, livestock, and wildlife. The transport of soil particles into and through aquatic systems, called sedimentation, is an important ecosystem process that can have both positive and negative consequences depending on its scale and other factors. On the positive side, soil particles provide substrates for living organisms and for chemical reactions that affect nutrient cycling (Roden et al. 2010, Sathasivan et al. 2010). Some aquatic microbial communities require the surface areas provided by suspended solids and thus may increase with increased suspended solids (Moseman-Valtierra et al. 2010). However, at certain quantities and with particles of certain texture, sediments deposited in aquatic systems begin to negatively impact the suitability of the habitat for many types of aquatic fauna (Moseman-Valtierra et al. 2010, Larsen & Ormerod 2010). Native salmonids, for example, require gravel substrates that are relatively free of fine sediments in order to spawn successfully (Markus 2011, Sternecker & Geist 2010, Wiseman et al. 2010). In general, suspended sediments impede light penetration through the water column, which may favor algal and phytoplankton growth over macrophyte productivity (Leston et al. 2008). Deposition of sediments reduces the capacity and life-span of stock ponds as accumulated solids displace water storage space. Suspended particles also reduce water clarity, which may be an important issue for some managers.

Rates of sedimentation are governed by many factors that are out of our control, such as size of watershed, soil type, slope, and regional precipitation levels, but there are also many important factors, such as vegetative cover, that can be influenced by livestock management. Human activities have greatly increased rates of sedimentation globally, and in many localized cases this has been to the detriment of important water quality (Schlessinger 1997). Thus, mangers often seek to reduce rates of sedimentation.

Livestock may influence sedimentation rates via two main processes: physical interaction with soils and interactions with vegetation. Prolonged high-density grazing can lead to soil compaction, which reduces watershed permeability (Agouridis et al. 2005, Tate et al. 2004). Reduced permeability, in turn, ultimately increases the volume of surface runoff, which is a major driver of sediment transport (Agouridis et al. 2005). Trampling by livestock in sloped areas adjacent to water sources may lead to increased displacement of soil through shearing or increased volume and velocity of water entering the stream channel (George et al. 2004, Agouridis et al. 2005). It is important to note that while livestock use has frequently been implicated in watershed erosion, one of the biggest sources of sediment in rangelands is roads and trails (George et al. 2004).

Interactions between livestock and vegetation and the subsequent outcomes in terms of soil displacement and sedimentation are complex and highly dependent on context. On the one hand, it is well documented that vegetative cover is negatively correlated with sedimentation—that is, the greater the vegetative cover the less the sedimentation (Cerdan et al. 2010, Cotton et al. 2006, Tate et al. 2004). Through their consumption of plants, livestock can reduce vegetative cover, which may cause increased sedimentation. The magnitude of this effect varies widely depending on stocking intensity, the type of livestock, and the timing and duration of grazing (Bartley et al. 2010, Tate et al. 2004). For example, sheep tend to stay away from surface waters more than cattle. With California's Mediterranean climate and annual grasslands, livestock spend more time in the uplands during the spring growing season than during the dry warm summer. Without alternative forage and water sources, livestock may concentrate in riparian areas during the dry season, increasing the risk of stream channel erosion (George et al. 2007). On the other hand, depending on the context, livestock grazing can influence vegetation in ways that can potentially *reduce* landscape erosion. Foraging by livestock, for example, can change the growth form of plants in the affected community, potentially leading to increased stem densities (Dalgleish & Hartnett 2009). In a long-term study on sheep grazing in the Inner Mongolian steppe, Zhen et al. (2006) found that plots exposed to light, moderate, or heavy grazing had greater total vegetative cover than plots with no grazing. These vegetation changes in response to grazing may reduce displacement of soil during rain events and thus reduce sedimentation.

Nutrient and Chemical Dynamics

The movement of key nutrients such as nitrogen and phosphorus through the different parts of the environment—biomass, soil, sediments, and water—is an important part of many ecosystem processes and may have far-reaching consequences for watersheds. This section focuses on nitrogen and phosphorous because they are major limiting nutrients in both terrestrial and aquatic ecosystems (Schlessinger 1997). As such they are vital in maintaining the productivity of food webs including those in which livestock are important consumers. In general, a certain level of phosphorous and nitrogen in the soil is necessary for sustaining primary productivity and thus potential for livestock weight gain. On the other hand, however, enrichment with labile forms of these limiting nutrients may lead to undesirable changes in the community composition of terrestrial and aquatic systems.

The dynamics of these elements are important in two key ways. First, both can contribute to eutrophication when high levels of their biologically available forms are released into surface waters (Schlesinger 1997). Second, some forms of nitrogenous compounds can present health risks when consumed in drinking water and are thus considered contaminants (Chang et al. 2010). As described by Schlesinger (1997), nitrogen and phosphorous are similar in that they are both limiting nutrients for a great variety of organisms and occur naturally in several different forms that are more or less biologically active, but there are some key differences in their cycling. The main pool of phosphorus is within soils and in less-weathered parent materials, where it occurs in solid mineral compounds. It may also occur in smaller amounts dissolved in the water contained in the soil. The main pool of nitrogen is atmospheric, and portions of the biologically active pools are frequently returned to the atmosphere throughout its cycling. Because it has gaseous forms and because some of its mineral forms are highly soluble, nitrogen can be highly mobile.

Livestock can be an important part of nitrogen and phosphorus cycling in watersheds. A portion of the landscape’s biologically active nitrogen and phosphorus is taken up by livestock as these animals consume forage plants. Some of that pool is ultimately exported from the system in the form of livestock tissues during harvest. Some of it is released back into the system in highly soluble form as solid and liquid wastes are deposited throughout the animal’s residency in the landscape. The subsequent movement of this nitrogen and phosphorus presents a potential threat to water quality. If the amount of these nutrients deposited in livestock wastes exceeds the capacity for terrestrial plants and soils to absorb them, residual components may enter ground water or streams, where they can contribute to nitrate contamination or eutrophication (Derlet et al. 2010).

On the other hand, the presence of livestock can have positive results for nitrogen cycling. Nitrogen enrichment from air pollution is increasingly being recognized as a serious problem in many regions, including some parts of the Central Coast, because it may promote the growth of weedy, non-native vegetation and negatively alter ecosystem dynamics. Because they consume the nitrophilous plants that absorb the labile nitrogen from air pollution, cattle may be an effective means of removing some of this excess nitrogen input and thereby mitigating its impact on affected communities (Weiss 1999). In a different study, Jackson et al. (2006) found that spring-fed herbaceous wetlands in California's foothills had lower nitrate concentrations when moderately grazed than when they were left un-grazed. The authors attributed this difference to enhanced nitrogen uptake by plants and enhanced rates of microbial denitrification in the sites grazed by cattle. While the stimulated denitrification may be unique to moist ecosystems, enhanced nitrogen uptake by plants in grazed systems may be more widespread.

Biotic Components of Water Quality

There are many biotic components of water quality and these interact dynamically with the abiotic components described in the previous sections. Several types of aquatic protozoa, bacteria, and algae may compromise the suitability of water for human or livestock consumption. I focus first on water-borne pathogens and parasites and how livestock management may affect their presence in water sources.

Protozoa such as *Giardia* spp. and *Cryptosporidium* spp., as well as bacteria such as *E. coli*, may be carried by livestock, introduced to surface waters, and subsequently spread to humans or other livestock through exposure to contaminated waters. The presence of these organisms in water sources is of serious concern because of their potential to cause health problems for humans or livestock and the cost associated with treating the water to remove the organisms (Olsen et al. 1995, Olsen et al. 1997, Anderson 1991, Tate et al. 2000). The major focus for managing these biotic contaminants is minimizing fecal contact with water sources (Willms et al. 2002, Tate et al. 2000). Since livestock commonly host these gastro-intestinal parasites, and because infected animals' fecal matter usually contains the parasites' oocysts, reducing livestock fecal inputs to surface waters should reduce the risk of humans or uninfected livestock being exposed to them (Willms et al. 2002, Tate et al. 2000). It should be noted, however, that the risk of transmitting and shedding these parasites may vary over the year according to animals' reproductive cycles. Hoar et al. (2001) found that calves were more likely to shed *Cryptosporidium* than adults and that a longer calving season was associated with a greater proportion of cows with this parasite. Another study showed that ewes shed more *Cryptosporidia* and *Giardia* oocycsts around the time of giving birth (Xiao et al. 1994).

Under some circumstances algae may present problems for water quality. Algal dynamics are an important rangeland management consideration because highly labile nutrient inputs from livestock may contribute to rapid growth of algae. Subsequent eutrophication can affect the suitability of the aquatic habitat for wildlife, and some algae may produce chemical compounds that affect the suitability of water sources for human or livestock consumption. Eutrophication begins when nutrient enrichment leads to rapid growth of short-lived algae. As the tissue from this algal mass is decomposed by aquatic microbes, oxygen is depleted, creating an anoxic environment that is inhospitable to many other organisms (Mitsch & Gosselink 2000). Since native salmonids and many stream invertebrates require relatively high levels of dissolved oxygen, a stream with any level of eutrophication may cease to support them (Wiseman et al.

2010). Some blue-green algae may produce toxins that render water unsuitable for livestock and many produce aromatic compounds that affect the palatability of the water (Willms et al. 2002). In a study that compared the effects of water quality (low-algae trough water vs. higher algae pond water) on cattle performance, Willms et al. (2002) found that calves of cows that had access to the cleaner water had 9% greater weight gain, while yearling heifers with access to cleaner water had 20–23% greater weight gain. They observed that cows with access to clean water spent more time grazing and less time resting and that when given a choice, these animals avoided water contaminated by more than 0.005% (by weight) fecal matter.

Management for Better Stewardship of Watersheds

While it is useful to consider specific interactions separately to understand the relationships between livestock and water quality, these processes are not independent. Management modifications that target one aspect of water quality will invariably influence other parameters. In some cases, attempts to realize one management goal may end up undermining another. Therefore, while discussing management strategies that may be implemented to protect water quality, this section also notes how each strategy may affect multiple parameters at once.

In general, actions that minimize contact between livestock and sensitive water resources should be beneficial to water quality, but these may have varying degrees of feasibility depending on the manager’s operational objectives and the resources available for implementation. Appendix 1 contains a summary of key research findings that are related to management of livestock for water quality. The University of California Cooperative Extension and the US Department of Agriculture Natural Resources Conservation Service offer informational, technical, and financial assistance to help land mangers carryout planned actions to protect water quality in their stewardship of rangelands (George et al. 2011)

An important part of improving management is having appropriate metrics or indicators of management outcomes by which the success of strategies can be evaluated. In the case of water quality, many important parameters can be difficult to measure directly. Measuring microbial populations or nutrient levels, for example, generally requires biological and chemical lab equipment. However, much work has been done to establish meaningful indicators of rangeland health, many of which have a direct relationship to water quality. Residual dry matter (RDM)—the amount of crop residue left on the range—has become widely recognized as an informative and simple metric of range health (Bartolome et al. 2002, Bartolome et al. 2007). While RDM does not directly infer water quality, it is related to many factors that influence water quality within rangelands (Bartolome et al. 2002).

The temporal and spatial distribution of livestock (where livestock range and during what times) is of fundamental importance in protecting water quality on rangelands. While much of the literature reviewed here suggests that limiting livestock access to surface waters is the primary strategy for minimizing the impacts on water quality, the effects of livestock on water quality are partly dependent on the season and duration of exposure. Furthermore, for some management scenarios it may be desirable to allow livestock to access areas containing surface waters. Managers may wish to utilize forage in these areas, may rely on them as drinking sources for livestock, or may be inclined to use livestock for weed control around these areas. In each of these cases, an understanding of the role of timing and distribution may be helpful in minimizing the impact of livestock on water quality.

Excluding livestock from sensitive riparian areas and springs with vegetated buffers can minimize stream bank erosion, sediment loading, the spread of fecal-borne pathogens, and nutrient inputs to water (Ellison et al. 2009). Work by Tate et al. (2004) has demonstrated that vegetated buffers as little as one meter (~3 feet) wide significantly reduce the numbers of pathogenic *Cryptosporidium* oocysts that reach surface waters. Vegetated buffers are also important for nutrient capture. The capacity of buffers to take up mobilized nutrients in runoff may be enhanced by periodic removal of above-ground biomass. Bedard-Haughn et al. (2005) found that clipped grass buffers around irrigated pastures sequestered 2.3 times the nitrogen absorbed by uncut buffers. The researchers attributed this effect to increased nitrogen uptake by the grasses as they grew more rapidly in response to cutting.

Fencing can be a valuable tool for manipulating livestock use of range and minimizing impacts to water quality. Fencing that separates uplands from lowlands can improve the manager's ability to utilize forage more evenly throughout the year and avoid disproportionate impact to riparian areas during the dry season (George et al. 2007). The development of fenced riparian pasture systems may be a good way to integrate use of these areas. Being able to control the timing and duration of access will be crucial in protecting water quality in these systems. There is currently a lack of scientific research on the management of riparian pastures but much insight could be gained from land managers who appropriately monitor their use of these systems (Ward et al. 2003). While fencing may be necessary to protect some sensitive resources during livestock use, it may be impractical and un-necessary for meeting many other rangeland water quality goals.

A variety of methods other than fencing can be used to affect animal distribution in ways that protect water resources. Providing strategically placed alternate water sources for livestock can reduce the amount of time that animals spend near sensitive surface water resources. In addition to seeking the water provided by alternate sources such as troughs, livestock will tend to forage near these areas. If managers can control the availability of water at multiple sites in the range, they can do much to influence movement and distribution of their animals (George et al. 2007). Supplements such as mineral licks or molasses can also be used to attract livestock and encourage their movement to areas targeted for use. Positioning of these attractants should be strategic so as to minimize barriers and travel distance to livestock water sources (George et al. 2007). The areas immediately near attractants will be subject to high use, which can lead to defoliation, compaction, and high rates of feces deposition (Tate et al. 2003). For these reasons, sites should be chosen carefully and sources should be mobile when possible.

Conclusion

Water is among the most crucial of life's resources and we rely on healthy, well-functioning watersheds to capture, cleanse, and yield water for our use and to enable ecosystems to provide us with important ecosystem services. Ranchers and the managers of public lands on which grazing occurs make decisions and take actions that influence large areas of our watersheds. Their ability to manage livestock in a way that maintains sufficient water quality both within and beyond these managed lands depends on their having an understanding of the potential interactions between livestock and water quality.

Livestock should be viewed as an integral and dynamic component of these working landscapes. In addition to being part of our agricultural systems, livestock are increasingly being recognized for their value in meeting a variety of management goals. Regardless of the intended use of livestock by different land managers, these animals have great potential to influence water quality for good and for ill because of their ability to alter physical, chemical, and biotic components of the ecosystems in which they exist. Informed consideration of these dynamics can help land managers better integrate water quality objectives with other management goals such as optimizing animal weight gain, reducing levels of standing fuel, or meeting biodiversity targets. It is equally important to recognize when there may be tradeoffs involved and how it may be possible to meet multiple goals without balancing tradeoffs.

Land mangers and researchers have worked hard, in somewhat different ways, to understand the interactions between livestock and the landscape and how these interactions influence our water quality. Scientists employ a variety of analytical tools to understand the mechanisms of changes in rangeland watersheds and to keep the effects of manipulations separate from the effects of extrinsic and confounding factors. Land managers, in contrast, derive their knowledge from years of hands-on experience and intimate observation of changes and patterns under different resource-use scenarios. Continued open dialogue and collaboration between scientists and land managers will be crucial for achieving sound stewardship of water resources through wise rangeland management.

Acknowledgements

This work was funded by a Resource Management Grant from the Midpeninsula Regional Open Space District for the CCRC's Manager and Scientist Forum on Rangeland Conservation. The author appreciates the editorial assistance of Eric W. Engles, PhD (eric@editcraft.com).

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Appendix 1.

A summary of key research findings on managing livestock to protect water quality.

Water Quality Parameters	**Key research findings for management strategies**
General	Attractants such as alternate water sources (ponds or troughs) and supplements (mineral licks, molasses, etc) are valuable tools for influencing where animals spend their time and can minimize impacts to water from heavy use of sensitive areas while reducing reliance on extensive fencing (George et al. 2007, Tate et al. 2003).
Pathogens	Densely vegetated herbaceous buffers (> 95% cover) of as little as one meter (~three feet) can substantially reduce pathogen movement into surface water (Tate et al. 2004). Such buffers can generally be established by fencing to exclude livestock.
Nutrients	Cutting grass buffers to remove biomass can strongly enhance the capacity of buffers to absorb nitrogen from runoff because it stimulates plant growth and associated nitrogen uptake (Bedard-Haughn et al. 2005)
Pathogens	Calves (< 4 months) shed common pathogens such as *Cryptosporidium* at greater rates than older animals and calving occurs when transfer of these pathogens to the watershed and between animals is high. (Drake et al. 2001, Hoar et al. 2001, Xiao et al. 1994). Young calves should therefore be excluded—by timing of the grazing operation or by fencing and buffers—where and when they could be exposed to waters that are a source for human use.
Pathogens	Minimizing the handling of livestock during calving can reduce rates of pathogen transfer between animals (Hoar et al. 2001).
Sediment & erosion	While it is recognized that livestock can contribute to stream bank erosion, roads and trails may be a more important cause of erosion and sedimentation in rangelands than the activity of these animals. Trail formation by livestock can be minimized by reducing distances between watering areas and between water sources and feeding areas. (George et al. 2004). Establishing off-stream watering sources can also help reduce the stream bank erosion associated with livestock making trails into stream channels.
Nutrients	In California's annual rangelands, nitrogen uptake by plants takes place primarily within two periods during the growing season: September–November and February–April (Jackson et al. 1988). Use of livestock grazing to remove nitrogen from the system as described by Weiss (1999) should be most effective during these times. This approach is mechanistically similar to the clipping and harvest described by Bedard-Haughn et al. (2005), but more research is needed to determine whether this leads to significant reductions in the amount of nitrogen that reaches water resources.

Appendix 2.

A glossary of key terms used in this paper

abiotic: Processes or properties of the environment, such as erosion from moving water or the chemical composition of runoff, that are attributed most directly to non-living entities.

anoxic: Depleted of oxygen.

biotic: Processes or properties of the environment, such as the capture of nutrients from runoff by living plants, that are attributed most directly to living organisms.

denitrification: A natural process, often carried out by soil or aquatic bacteria, by which mineral nitrogen is ultimately returned to its gaseous form. This process can be important for water quality because it is one way that nitrogen contamination can be removed from water.

ecosystem services: Goods or processes that derive from the functioning of ecosystems and on which human beings rely, either directly or indirectly; important ecosystem services include forage production and the capture and cleansing of water by watersheds.

eutrophication: A process by which oxygen is depleted in a body of water after the water is enriched with excess nutrients. Short-lived algae grow rapidly in response to the increase in available nutrients, and the organisms that consume these algae use up much of the water's dissolved oxygen, leaving the water inhospitable to other organisms.

forbs: Broad leaved, non-grass herbs such as wildflowers.

herbivory: Consumption of plants by animals

labile: Readily usable or mobile, less stable. Some forms of phosphorus, for example, are considered labile because they are readily absorbed by plants or transferred to other pools, while other forms of this nutrient may be relatively stable.

limiting nutrient: A nutrient that is lacking relative to other essential nutrients. Increases in limiting nutrients typically lead to increases in the growth and/or reproduction of the consuming organism, because by definition all other necessary nutrients are present in sufficient levels to accommodate growth.

macrophyte: Larger aquatic plants (as compared to algae).

nitrophilous: Literally “nitrogen-loving.” Nitrophilous organisms respond strongly and quickly to increases in nitrogen.

oocyst: A life stage of some parasitic organisms that is often important for dispersal and transmission. Oocysts of *Giardia spp*. can be excreted from within their host in feces and subsequently transported to water where other hosts may be infected when they consume that water.

substrate: The medium on which an organism lives or on which a chemical reaction takes place (e.g., salmon lay their eggs in gravel substrates).