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U.S. GEOLOGICAL SURVEY

Proceedings of the U.S. Geological Survey Front Range Infrastructure Resources Project Stakeholder's Meeting

November 4, 1998

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November 1998

FRONT RANGE INFRASTRUCTURE RESOURCES PROJECT

STAKEHOLDER'S MEETING

TECHNICAL PROGRAM
WEDNESDAY, NOVEMBER 4, 1998

8:30 a.m. to 9:00..Welcome and Introduction

9:00 to 10:00...........................Decision Support System (DSS) demonstration

10:00 to 10:15..Break

10:15 to noon.....................................Poster Session, authors in attendance

Noon to 12:30 p.m..Next Step and Wrap-up

CONTENTS

INTRODUCTION

Infrastructure, including roads, airports, water and energy transmission and distribution facilities, and sewage treatment plants, is critical to the vitality and sustainability of a populated area. Because much of the infrastructure in the United States is old, having been built forty or more years ago, it has deteriorated to the point that extensive repair and replacement are required. Maintenance of a region's existing infrastructure, as well as development of new infrastructure to meet the needs of a growing urban area, requires large volumes of natural resources such as aggregate (principally stone, sand, and gravel), water, and energy. Sufficient resources may not, however, be available for use because of the 1) scarcity of local sources, 2) inaccessibility of resources (gravel cannot be mined from under a subdivision), or 3) unsuitability of the resources (polluted ground water may be unfit for use as a domestic water supply). The challenge for communities then is to be aware of their ongoing needs for infrastructure resources and to factor resource availability into planning for the future.

The U.S. Geological Survey's Front Range Infrastructure Resources Project (FRIRP) has been designed, with input from interested stakeholders, to provide objective information about the location and characteristics of land, aggregate, water, energy, and biological resources in the Front Range. This volume--The Proceedings of the U.S. Geological Survey Front Range Infrastructure Resources Project Stakeholder's Meeting, November 4, 1998--contains abstracts describing preliminary work in progress by FRIRP scientists and technicians from various disciplines including geology, hydrology, biology, and land characterization. The objective of the meeting is to bring together interested parties to discuss land, aggregate, water, energy and biological resources availability and quality in the Front Range urban corridor and to demonstrate a decision support system.

The Front Range Infrastructure Resources Project – An Overview

William H. Langer, Neil S. Fishman, Daniel H. Knepper, Jr., David A. Lindsey, Carol S. Mladinich, L. David Nealey, Stanley G. Robson, James E. Roelle, and David R. Wilburn

Infrastructure, such as roads, airports, water and energy transmission and distribution facilities, sewage treatment plants, and many other facilities, is vital to the sustainability and vitality of any populated area. Much of the Nation's infrastructure built during the 1950's and 60's has deteriorated to a point that extensive repair and replacement are required. In many areas of rapid population growth, even recent infrastructure may be inadequate and new infrastructure must be constructed to meet growing needs. Rehabilitation of existing and development of new infrastructure require three natural resources: natural aggregate (stone, sand and gravel), water, and energy. Despite the dependence of society on infrastructure resources, urban expansion often works to the detriment of the production of these essential raw materials. As urban areas expand, local sources of these resources become inaccessible (gravel cannot be mined from under a subdivision, for example), or the cost of recovery of the resource becomes prohibitive (oil and gas drilling in an urban area is costly), or the resources become unfit for some uses (pollution of ground water may preclude its use as a water supply). Further, land-use decisions and mandates by Federal, state, and local governments preclude development of resources in some areas. Resources that are unavailable locally must be imported from more distant sources, often at greater cost. Failure to plan for the protection and extraction of infrastructure resources often results in increased customer cost, environmental damage, and an adversarial relationship between industry and the community. Increased costs of maintaining or expanding infrastructure commonly are passed on to the public as higher taxes or reduced services in other areas. Well-reasoned decisions about land-use are critical to the National interest if infrastructure resources are to remain economically available.

The principal goals of the U. S. Geological Survey Front Range Infrastructure Resources Project (FRIRP) are to develop information, define tools, and demonstrate ways to 1) implement a multidisciplinary evaluation of the distribution and quality of a region's infrastructure resources, 2) identify issues that may affect availability of resources, and 3) provide (by working with cooperators) decisionmakers with tools to evaluate alternatives so as to enhance decisionmaking. A regional inventory of the resources needed for development and growth can define the basic physical resource limitations. Process studies can relate resource inventories to resource models and availability and can relate resource extraction to potential impacts on the environment. Geographic integration of data (geospatial databases) can provide an interactive tool to facilitate decision-making by stakeholders. Frequent interaction with stakeholders, including state and local agencies and the producers and users of infrastructure resources, can ensure a focus on the highest priority issues and can enhance the relevance of Project products.

The goals of the FRIRP are being implemented through 1) a three-year study of a demonstration area in the northern Colorado Front Range urban corridor; and 2) an overlapping, five-year study of the entire Rocky Mountain Front Range urban corridor from Cheyenne, Wyoming, to Pueblo, Colorado; the objectives will be pursued in conjunction with state and local groups. The structure of data sets, development of analytical models, construction of tools to spatially analyze data, and the approach to building state and local teams provide a pattern for similar work elsewhere in the United States.

The FRIRP is conducting studies of aggregate, energy, water, and biological resources.

- Studies of aggregate resources include identification, characterization, and modeling of aggregate using traditional field techniques, as well as remote sensing and geophysical studies. Environmental and reclamation issues related to aggregate development also are being investigated. Our principal cooperators for aggregate studies are the Colorado Geological Survey, the National Stone Association, and the Colorado Rock Products Association and some of its members.
- Studies of petroleum resources address issues related to the distribution, production, and future extraction of oil and gas resources. Environmental studies are underway to determine the relationship, if any, between water produced during oil and gas extraction and the formation of salt deposits in soils. The project is also investigating the distribution, extent, and depth to abandoned coal mine workings as related to coal mine subsidence. Our principal cooperators for energy resource studies are the Colorado Geological Survey and the Colorado Oil and Gas Conservation Commission.
- Because water resources are required to sustain a growing infrastructure, the FRIRP is defining the extent and character of the ground-water supplies in the project demonstration area. Specifically, we are producing maps showing the extent, thickness, water table, and water quality conditions of the shallow aquifers, as well as the interconnection between shallow aquifers and deeply buried bedrock aquifers in the region. Our principal cooperators for water resources studies are the Colorado Water Conservation Board and the Colorado Department of Natural Resources, Division of Water Resources.
- Biological resources, such as riparian (streamside) areas of the Front Range provide important wildlife habitat and significant human amenities. In places, they also overlie natural resources such as aggregate or water resources. Extracting mineral or water resources may impact habitats. Conversely, post-extraction reclamation may allow enhancement of habitat values. Evaluation of such consequences requires objective, current biological data. Similarly, commercial and residential developments often conflict with infrastructure resource extraction and habitat values. The FRIRP is studying the relative economic value of a variety of land use and resource development options. Our principal cooperators for biological resource studies include the Colorado Division of Wildlife, the Colorado State Heritage Program, the University of Colorado, and Western Mobile, Inc.
- Identification of land use and landscape conditions, and the processes that change those conditions, is essential to management of infrastructure resources. Therefore, we are collecting data to evaluate land-surface characteristics such as topography, soils, vegetation, and historical and existing land-use. We are also developing Geographic Information System applications to manage and display these data, and a Decision Support System to demonstrate the usefulness of the data.
- Communication and exchange of information with stakeholders is necessary to ensure maximum benefits from the FRIRP. We have an aggressive outreach program and are conducting our outreach activities in cooperation with a number of State and local government agencies and with industry representatives.

Geologic and Environmental Factors in Reclamation

Belinda Arbogast

Classic and unusual reclaimed mine sites from around the world and in the United States have been evaluated regarding the sites' physiography, ecology, function, artistic form, and public perception. An investigation of the history of mine resource management, regulatory considerations, landscape change and cultural considerations, and aesthetics from an ecological perspective, was undertaken. Given the limited research available on past and current landscape practices in aggregate resource development, an annotated bibliography on site design, environmental factors and regulations, and land use planning in mined land reclamation was published (Open-File Report 98-144).

Examining selected sites suggested a model for nine design approaches in mining reclamation. Nature, camouflage, restoration, rehabilitation, mitagation, recycling, education, art, and integration approaches were characterized. A paper has been accepted by the Oklahoma Geological Survey for publication concerning the design approaches. Visual aspects of landscape change from human-anthropogenic movement of earth, especially surface mining, are being analyzed for natural patterns (including form, space, and order) so that "aesthetics" can be defined from a scientific as well as philosophical view.

A collection of photographs has been inventoried for future reference. We believe this information is useful for land planners, industry, academia, and the public.

A Computer Model to Determine the Most Likely Areas for Future Drilling in the "D" and Muddy ("J") Sandstones, Wattenberg Field, Colorado

Troy Cook
U.S. Geological Survey

The Wattenberg gas field in the Front Range of Colorado (Fig. 1) covers an area of approximately 700,000 acres and has multiple oil and gas producing horizons. The primary natural gas producing formations in this field are the "D" sandstone of the Benton Shale and the Muddy "J" Sandstone of the Dakota Group. Oil and natural gas are also produced in this area from the Codell Sandstone, Niobrara Formation, and sandstones in the Pierre Shale. Based on a table of Estimated Ultimate Recovery's (EUR's) of natural gas (D. Cox, written communication, 1998), a model has been developed that finds the highest potential undeveloped acreage in the field. This model is run with a specific set of variables, which can be changed. Some of the variables include spacing considerations, estimated average drainage radius per million cubic feet of natural gas, and the timing and pace of the expected drilling. By changing these parameters individually and running the model multiple times it is possible to see how individual assumptions might affect future development of this area.

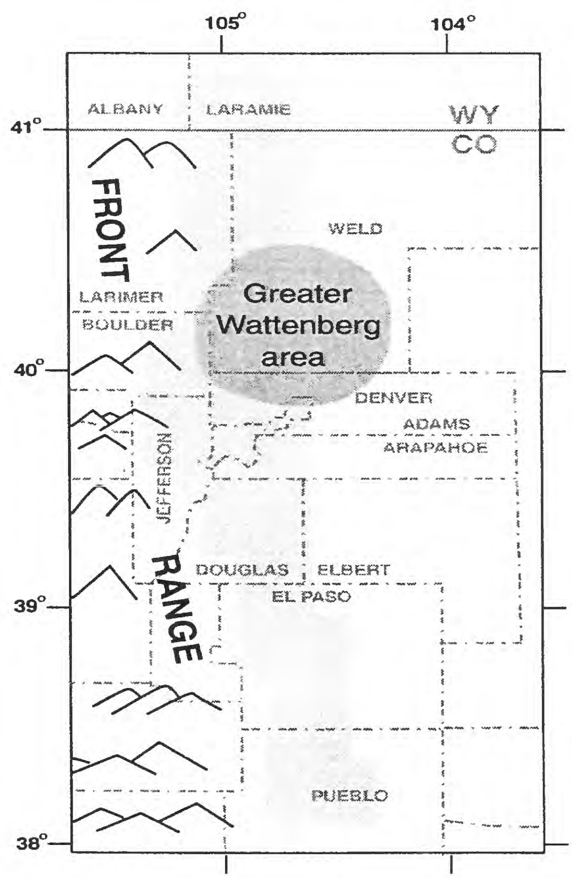

Figure 1. Map showing the locations of the Front Range Infrastructure Resources Project area, (light shading) and of the greater Wattenberg area, (dark shading) where most of the oil and gas is produced within the project area.

The purpose of this model is to find areas of high potential that haven't yet been drilled, as well as existing wellbores with high potential for recompletions and drilldowns in other formations. To reach the "J" and "D" sandstones from existing wellbores in other producing formations, work must be done to either deepen or recomplete the existing wellbore. The economic advantage of recompleting or deepening an existing wellbore versus drilling a new hole can be substantial.

The basic assumption for this model is that the EUR of natural gas is a good indicator of producing potential for a given area. By considering multiple EUR's within a given area and using a distance-weighted averaging formula to approximate potential EUR's, a reasonable value can be obtained for any undrilled acreage within the field. A reasonable value for existing wellbores can also be obtained using the same method.

This method of evaluating a given area was applied in a 50 meter by 50 meter grid pattern to all acreage across the entire Wattenberg field. Grid cells were removed for acreage that had already been drilled and in which gas production in wells was depleted. The evaluated grid cells were then ranked from largest to smallest potential EUR.

By changing some of the basic parameters listed above and rerunning the model it is possible to determine a range of outcomes. Areas that the model develops consistently, regardless of assumptions, are very likely targets for future development in the "D" and Muddy "J" Sandstones.

Geophysics in Exploration for Sand and Gravel

Karl J. Ellefsen, Jeffery E. Lucius, and David V. Fitterman[1]

A geophysical investigation can provide valuable geologic information needed to characterize sand and gravel deposits and can be an attractive complement to more common characterization methods like drilling. Although such investigations have already been conducted, a comparison of the different geophysical methods used in these investigations apparently has never been done. For this reason, a study was initiated by the Mineral Resources Program of the U. S. Geological Survey. The goal is to determine the advantages and the limitations of different geophysical methods when used to evaluate alluvial sand and gravel deposits. The study is focused on those geophysical methods that are commonly available because these are most likely to be used by industry. Furthermore, the study is focused on surface geophysical methods.

Heretofore, four different methods have been evaluated. Three of the four methods — time-domain electromagnetic soundings, frequency-domain electromagnetic profiling, DC resistivity soundings — are similar in that they all measure the electrical resistivity of the ground with depth. Ground penetrating radar, however, maps changes in the dielectric permittivity and/or the electrical resistivity with depth. For all four methods, the objective is to relate the measured physical quantity to the stratigraphy of the alluvial sediments.

The study was conducted at two sites in the South Platte River valley, northeast of Denver, Colorado. One site was adjacent to an active sand and gravel pit, where the sediments and the underlying bedrock are well exposed. These alluvial sediments are roughly 7 m thick and consist of gravel, sand, and some clay. The bedrock beneath these sediments is mudstone. The water table is within the alluvial sediments — there are roughly 6 m of unsaturated sediments and 1 m of saturated sediments. The thickness of the unsaturated sediments was accurately determined with the time-domain electromagnetic soundings (Figure 1) and the DC resistivity soundings (Figure 2); the thickness was determined moderately accurately with the frequency-domain electromagnetic profiling. The thickness of the saturated sediments could not be determined with any of the tested methods because its electrical conductivity is practically identical to that of bedrock. Sedimentary structures, such as foreset beds, were detected with ground penetrating radar; the bedrock surface was possibly detected when a low-frequency, high-power radar antenna was used.

The other site was a transect across the entire South Platte River valley, and the subsurface geology here had been determined from 12 test holes. The alluvial sediments consisted of gravel, sand, and some clay, and the sediments are covered with soil that is 1 to 2 m thick. In the center of the transect, the sediments and the soil are between 9 and 16 m thick; on the western and the eastern sides, they are between 15 and 25 m thick. The underlying bedrock is mostly shale. Across the entire transect, the water table is believed to be 2 or 3 m below the ground surface. In the center of the transect, the combined

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thickness of the sediments and the soil was accurately determined with the time-domain electromagnetic soundings and the DC resistivity soundings. However, on the western and the eastern sides of the transect, the thickness could not be determined with either method; rather, layers in the alluvial sediments that are not present in the center of the transect were detected. Ground penetrating radar could not detect any sediments beneath the soil because the soil is clay-rich.

LAYER	RESISTIVITY (Ω-m)			
1	92 (56-240)	95 (59-220)	100 (63-240)	110 (63-280)
2	12 (11-14)	12 (11-13)	10 (9.4-11)	7.8 (7.5-8.3)
3	5.8 (5.5-6.1)	5.6 (5.3-5.8)	5.8 (5.5-6.1)	6.1 (5.6-6.4)

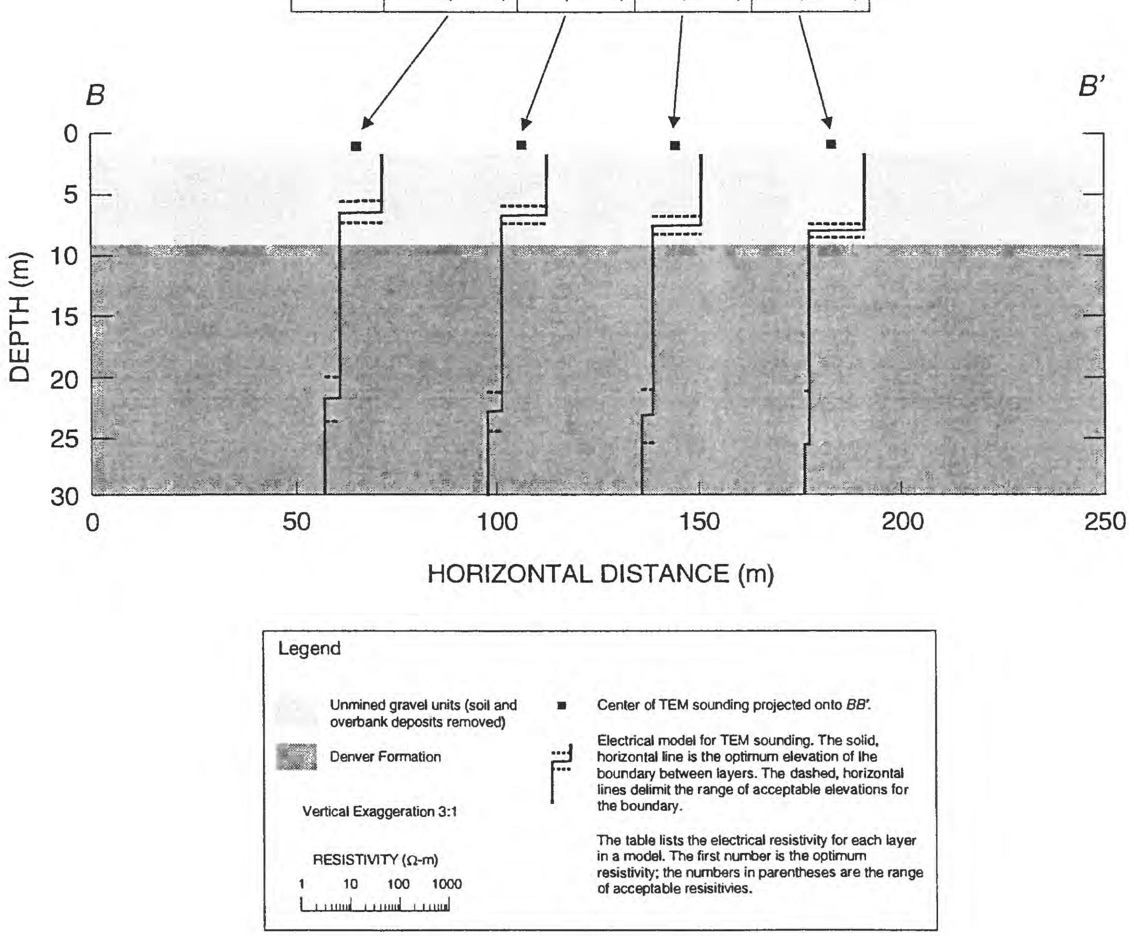

Figure 1. Cross section the Howe Pit and the electrical models from the TEM soundings.

LAYER	RESISTIVITY (Ω-m)						
1	1900 (1500-2300)	960 (850-1100)	390 (340-440)	1500 (1400-1700)	2100 (1900-2200)	550 (520-590)	5100 (4400-6100)
2	600 (540-650)	33 (21-46)	9.7 (7.7-12)	22 (17-28)	760 (610-910)	160 (98-280)	950 (600-1400)
3	31 (24-38)				9.2 (6.2-13)	4.8 (3.9-5.9)	27 (18-35)

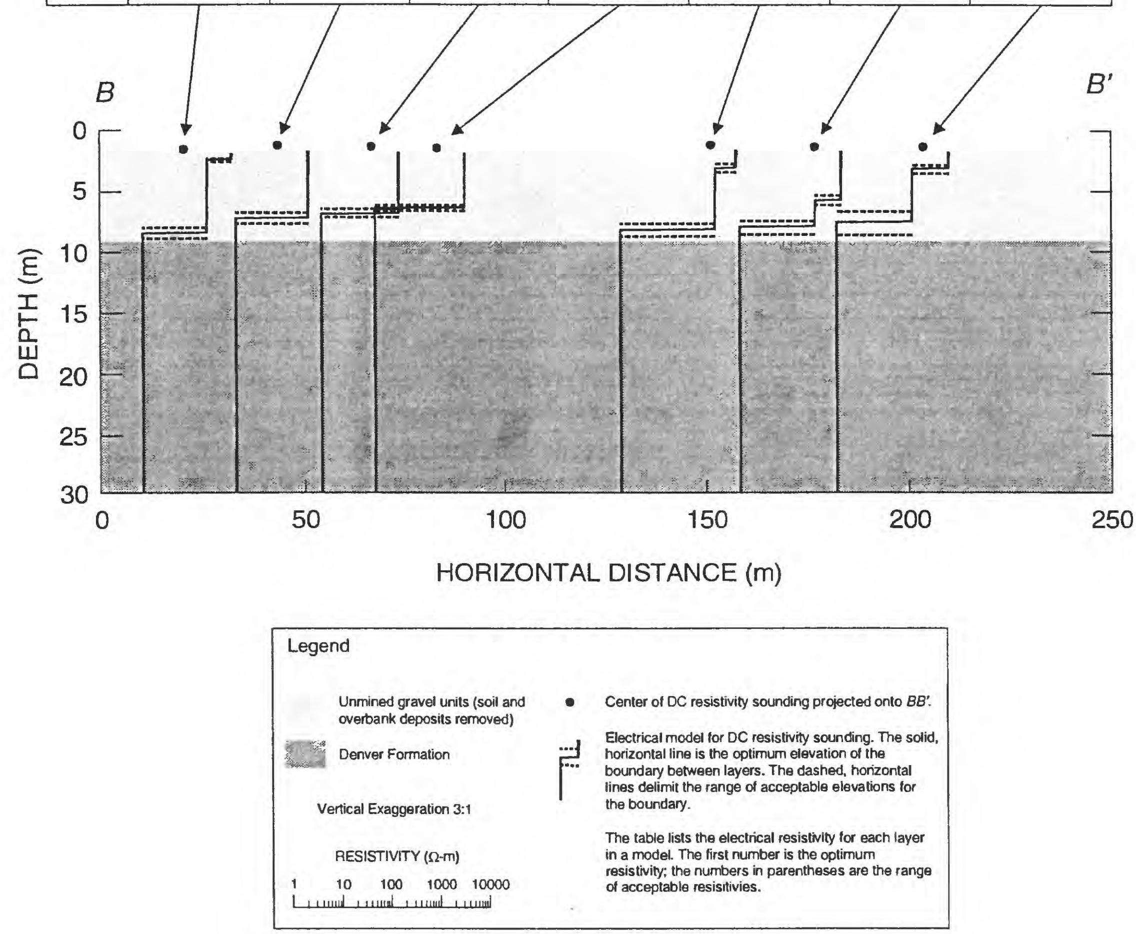

Figure 2. Cross section the Howe Pit and the electrical models from the DC resistivity soundings.

Influence of the Oil and Gas Production Infrastructure on Land Use in the Front Range of Colorado

Neil S. Fishman, Clark L. Woodward, and William H. Langer

INTRODUCTION

Production of oil and natural gas requires an infrastructure that includes 1) access roads to wells and other production equipment, 2) oil well pump jacks, 3) gas well heads, 4) pipelines, and 5) storage tanks. The land devoted specifically to this production infrastructure cannot be used for other purposes such as agriculture, urban and commercial development, or extraction of other natural resources (e.g. sand and gravel), at least not while oil and gas are being produced. More than 6000 wells currently produce oil and gas in the study area of the Front Range Infrastructure Resources Project (FRIRP) of the U.S. Geological Survey (figure 1). The necessary production infrastructure excludes a significant amount of land (>2300 acres or >3.6 mi^2) that could otherwise be used for other purposes. In this report we have estimated the area of land within the entire FRIRP study area devoted to the oil and gas production infrastructure as a function of land classification (e.g. agricultural, urban, rangeland, wetlands, etc.) and we also discuss how oil and gas production may affect development of other natural resources.

METHODS

The amount of land used for the oil and gas production infrastructure in the FRIRP study area has been estimated by combining direct field and computer-aided measurements. The dimensions of 24 pump jacks, 16 storage tank batteries, and 17 gas well heads were taken in the field to determine the land area devoted to the production infrastructure equipment in the greater Wattenberg area (figure 1); this is the region from which most of the oil and gas in the FRIRP study area is produced. The average land area of a pump jack, storage tank battery, or gas well head was then calculated. Based on the number of oil and gas wells in the FRIRP study area, the land area devoted to wells was then computed. Field observations led to an estimate of about one tank battery for every five oil wells, which then allowed for a rough approximation of the number of tank batteries in the study area; land area devoted to tank batteries was then calculated based on this approximation. Finally, the land area devoted to access roads was estimated using 1) field measurements of the width of access roads along with 2) digital measurements of the length of access roads made by measuring roads from digital line graph files of the Public Land Survey System (PLSS). Potential overlap of land areas between oil and gas wells and high quality aggregate resources was determined using simple spatial overlay and analysis. The spatial data were derived from the Petroleum Information Well History Control System database (1996) and aggregate maps from Schwochow and others (1974).

RESULTS

Access roads by far account for most of the more than 2300 acres (>3.6 mi^2) affected by the oil and gas production infrastructure, although a significant area of land is devoted to oil well pump jacks, storage tank batteries, and gas well heads in the greater Wattenberg area (Table 1). Access roads are typically about 10 ft wide, of varying length, and cover over 1700 acres of land in the FRIRP study area. In contrast, the land devoted to pump jacks (approximately 1000 ft^2 each) totals about 64 acres, the land devoted to gas well heads (approximately 100 ft^2 each) about 9 acres, and the land used for storage tank batteries about 520 acres.

Plotting the distribution of oil and gas wells on a base map of land use/land classification reveals that more than 90% of the oil and gas wells in the greater Wattenberg area are on agricultural land; most of the remaining wells are on rangeland and wetlands, and a few wells are on other types of land (figure 2). Although the plot of well distribution on land use suggests that there is only a small area of urban land devoted to the oil and gas production infrastructure, rapid urbanization and the drilling of many new wells in the past few years (post-dating the collection of the land use data) in areas north of Denver have resulted in new urban development in close proximity to or surrounding production equipment. Further, actions such as the decision by the City of Greeley to exclude drilling within city borders, precludes oil and gas development on at least some urban land in the study area.

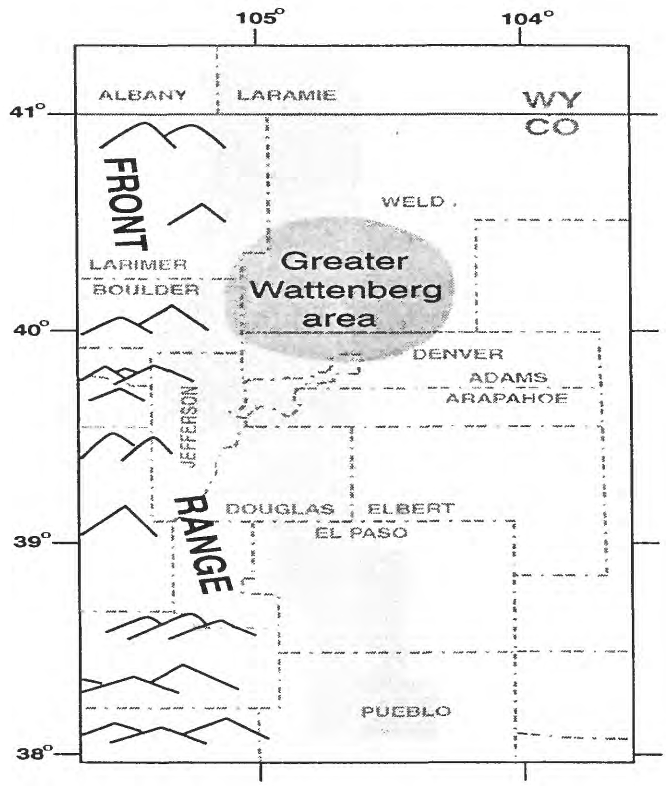

Figure 1. Map showing locations of the Front Range Infrastructure Resources Project area (light shading) and the greater Wattenberg area (dark shading), which is where most of the oil and gas is produced within the FRIRP area.

The oil and gas production infrastructure affects not only agricultural and urban areas but the extraction of other natural resources as well. As an example, many oil and gas wells in the greater Wattenberg area are in areas that contain aggregate resources that occur close to (within a few tens of feet) the ground surface. Oil and gas operators are owners of subsurface mineral rights and as such have ready access to land for development of oil and gas resources because mineral rights take legal precedence over surface rights. Use of the land for the oil and gas production infrastructure then renders this land inaccessible or restricted for full development of aggregate resources because the aggregate industry operates under surface ownership regulations.

Production Infrastructure Unit	Number of Units	Total acres used for units
Oil pump jack	~2800	67
Gas well head	~3600	9
Storage tank battery	~560	521
Access road	~6400	1725
TOTAL		**2322**

Table 1. Listing of the production infrastructure used to determine area of land dedicated to oil and gas production instead of use for other purposes in the Front Range Infrastructure Resources Project area.

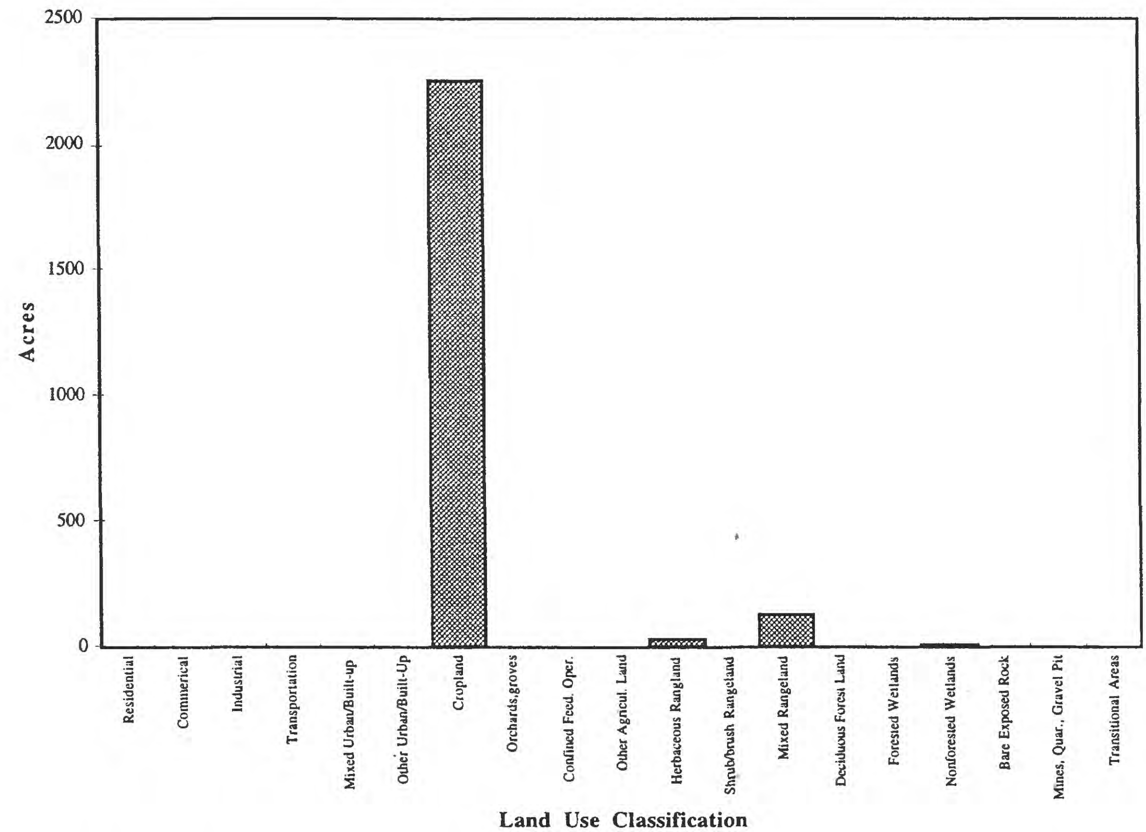

Figure 2. Chart showing the area of land occupied by the oil and gas production infrastructure as a function of land use classification in the Front Range Infrastructure Resources Project area. Classification after Anderson and others (1976).

DISCUSSION AND CONCLUSIONS

Much of the 2300+ acres (>3.6 mi^2) of land in the FRIRP area devoted to the oil and gas production infrastructure will continue to be used as such for at least another 30 years because that is the projected life of gas production in the greater Wattenberg area (Higley, 1998). Thus, much of the land currently devoted to the production infrastructure will continue to be excluded from use for other purposes during this period of time. While producing oil and gas, the land used for the production infrastructure cannot be used for other purposes (e.g., agriculture, urbanization, extraction of other infrastructure resources). The loss of use of agricultural land in the greater Wattenberg area is particularly important because this land is some of the most productive agricultural land in Colorado. Although, income to farmers may be lost, others benefit economically from production of oil and gas including operators and the public, through collection of taxes.

Competition for land in the Front Range of Colorado continues between those parties interested in future land use. Conflicts between oil and gas operators and surface owners (farmers, developers, and residents) have occurred in the past, but in some cases, disputes have been successfully resolved through negotiations between the interested parties. Nevertheless, rapid urbanization coupled with renewed exploration in the greater Wattenberg area may put developers and possibly the aggregate industry in competition with oil and gas production for use of the land. These conflicts may be an inevitable outcome when two or more parties are competing for the use of the land, but the conflicts can be minimized by improved communication and the increased use of detailed information about available resources.

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Survival of Plains Cottonwood and Saltcedar Seedlings in Response to Flooding

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U.S. Geological Survey

THE PROBLEM

Eurasian saltcedar (*Tamarix ramosissima*) was introduced into the United States as an ornamental during the 19th century but has since spread throughout southwestern riparian habitats. It is estimated that by the 1980's saltcedar dominated over one million acres of riparian areas in this geographic region. Saltcedar requires saturated soils for germination, as does native plains cottonwood (*Populus deltoides* subsp. *monilifera*), but often has a competitive advantage because of differences in its reproductive biology. Saltcedar can reach reproductive maturity in the first year following establishment and produces abundant seed throughout much of the growing season. In contrast, the minimum seed-bearing age of plains cottonwood is about 10 years, and the annual seed production period is much shorter. Once established, saltcedar is difficult and expensive to eradicate, although a combination of mechanical removal and herbicides has been used successfully on small areas.

Water manipulations (e.g., seasonal drawdowns) conducted to stimulate establishment of desirable plants frequently result in conditions that also are ideal for saltcedar establishment and growth. We encountered this problem during a riparian habitat restoration project at a sand and gravel mine (the WREN Pit) in Fort Collins, Colorado. Our water manipulations were successful in establishing cottonwoods and willows (*Salix* spp.), but also resulted in abundant saltcedar seedlings. During the fall of 1993 and spring of 1994, we reflooded the pit in an attempt to eliminate saltcedar. While we did not quantitatively monitor the results, by the summer of 1994 it was apparent that the control effort was at least moderately successful; most saltcedar seedlings were killed, and many cottonwood seedlings survived. We subsequently conducted a controlled experiment to verify and quantify these casual observations.

METHODS

In 1995, cottonwood seeds were first available locally on 23 June, and seed production lasted less than 3 weeks. Saltcedar began to produce seed about 17 July and continued into October. During July, we collected seeds of both species by picking branches and catkins bearing partially opened seed capsules. Materials were collected from twelve individuals of each species to help ensure genetic diversity. We filled 84 plastic horticultural pots (26.5-liter volume) with uncleaned sand, submerged each pot in water briefly to saturate the substrate, and placed them in water in the WREN Pit deep enough to keep the substrate surface moist (through capillary action) for seed germination.

Each pot was randomly assigned to one of three treatment groups by species; fall flooding, spring flooding, and no flooding (control). On 7 July, we sprinkled 40-50 plains cottonwood seeds on each of 42 pots, and on 27 July we shook seed-laden branches of saltcedar over the remaining 42 pots. Following germination, we gradually lowered the water level in the pit during August and early September to encourage root growth, and we irrigated the pots if the surface substrate became dry.

On 12 September we thinned all pots to a maximum of 18 seedlings. We believed that the resulting range of 12-18 seedlings/pot would help minimize between-pot differences in competition and provide a relatively continuous distribution of possible survival rates. On 15 September we submerged 14 plains cottonwood and 14 saltcedar pots to a depth (9 cm) sufficient to cover all saltcedar but not all plains cottonwood seedlings. The water level in the pit remained relatively stable during the fall treatment, which lasted 25 days. On 10 October we removed pots from the fall treatment and buried all pots at the study site for overwintering. The pots were placed with their perforated bases in contact with groundwater and the soil surface at ground level to help ensure adequate moisture availability and ambient soil temperatures.

Following leafout in the spring of 1996, we removed all of the pots from their overwintering sites, allowed them to drain overnight, and placed them in the WREN Pit with their bases in contact with water to maintain adequate moisture in the rooting zone. By the spring of 1996, water in the WREN Pit was too shallow to completely inundate pots for the spring treatment, so we selected a nearby site at Colorado State University's Environmental Learning Center. One saltcedar pot was damaged during transport to this site, so we reduced the number of spring treatment pots from 14 to 13 of each species. On 21 May we submerged the pots assigned to the spring flooding treatment, each containing 12 to 18 seedlings, to a uniform depth that inundated all saltcedar but not all cottonwood seedlings. However, within several days rising water in the pond completely overtopped all seedlings. The 26 pots remained underwater until 18 June (28 days), at which time they were moved to the shallow-water location of the other pots in the WREN Pit.

On 8 July we counted surviving seedlings in each pot. Seedlings were recorded as surviving if they had green foliage or pliant stems with green cambium layers. Survival rates for each pot were calculated for the period 12 September 1995 to 8 July 1996. Because there may be a relationship between turbidity (as it influences light availability) and seedling survival, we also measured photosynthetically active radiation at various depths in each of the treatment ponds at approximately noon on a cloudless day. We determined a light extinction coefficient for each treatment by fitting these data in a nonlinear regression.

RESULTS

Mean and median survival rates for seedlings flooded in fall were much lower than for those flooded in spring and for controls. We used multiple response permutation procedures to detect omnibus distributional differences in survival because assumptions of normality and equal variance were not met. Survival distributions differed between saltcedar and cottonwood fall flooding groups ($P < 0.0001$)

Table 1. Sample size (N), mean survival, and variance by treatment.

Treatment	N	Mean Survival (%)	Variance
Cottonwood control	14	98.7	6.43
Cottonwood fall	14	20.8	236.00
Cottonwood spring	13	92.2	63.60
Saltcedar control	14	93.9	167.43
Saltcedar fall	14	0.8	4.07
Saltcedar spring	13	91.1	142.46

and between fall flooding and control groups for both species ($P < 0.0001$). No differences in survival distributions were detected between species or treatments for the control and spring treatment groups ($P > 0.07$).

Water was more turbid in the fall flooding treatment (light extinction coefficient = 0.155 cm^{-1}) than in the spring (0.026 cm^{-1}). However, our data suggest that light relations alone are insufficient to explain differences in survival. Linear regression showed no relation between survival and mean percent of full sunlight reaching the tops of fall-flooded cottonwoods ($P = 0.63$). Adverse effects on root systems may have been the primary cause of differential seedling mortality. Fall flooding to control first-year saltcedar seedlings may be a useful management technique in some situations.

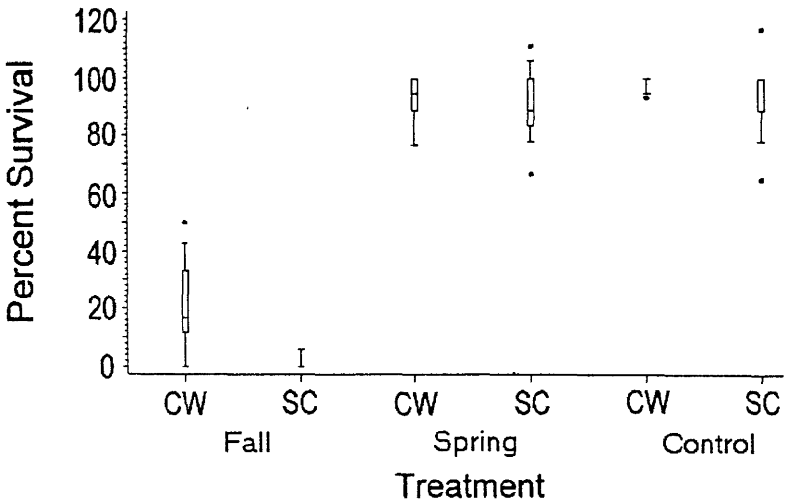

Figure 1. Distribution of seedling survival.

Element Concentrations and Water Solubility in Waste Fines Associated with Aggregate Production in the Front Range of Colorado

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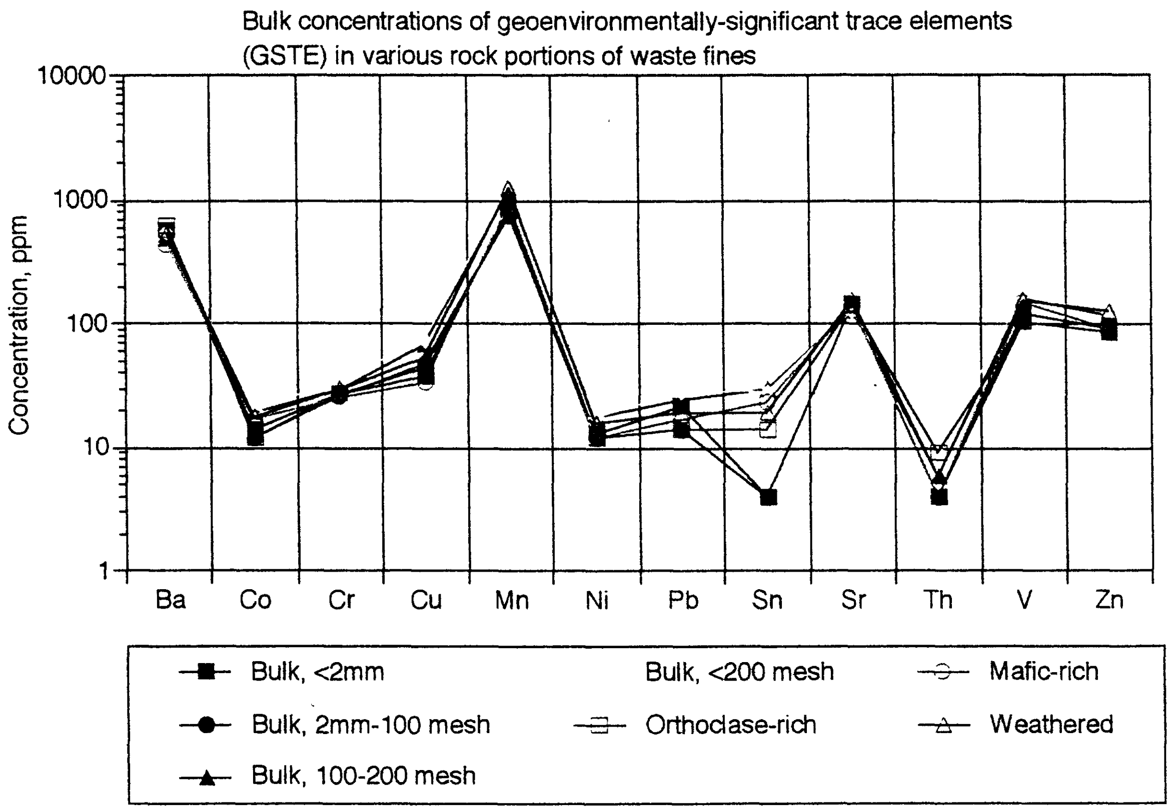
Fine-grained waste associated with aggregate production in the Front Range near Denver, Colorado, was sampled for its bulk composition and solubility of trace elements in water. The goal was to understand how this material might interact with the environment. The study focused only on the <2 mm portion of the fines, as the finer material has higher surface area and, hence, greater opportunity for trace element dissolution. Subordinate subsets of the <2 mm material included as part of the study were: (1) finer size cutoffs within the set; (2) subsampling of orthoclase- and mafic-rich material; and (3) weathered versus fresh rock. Samples were collected by incrementally sampling the surface of the various piles of waste fines to ensure statistical representation of the entire pile surface. The only compositional heterogeneity among the geoenvironmentally significant trace elements (GSTE) occurs for Sn, which is enriched by at least a factor of 10 in the two finer size classes. No significant concentration differences among the GSTE concentrations occurred for compositional differences or for weathered versus fresh rock. Concentrations of Co, Cr, Cu, Ni, Pb, Sn, and Th are generally well under 50 ppm. Concentrations of V and Zn are typically around 100 ppm in all samples.

Water solubility of various major and trace elements was determined on splits of the samples ground to < 0.15 mm. The water leach studies are a 24-hour passive leach using a water:rock mass ratio of 20:1. As there is little control on particle size distribution of this material, the water leach studies should be considered as only suggestive of solubility of the various elements. All extracts were near or above pH 9. Of the GSTE analyzed in the solid portions, most had solubilities less than 1 part per billion (ppb) in the leach studies. Only Ba, Mn, and Sr had solubilities above 1 ppb. Ba and Sr show greatest solubility in the weathered rock and from the finest size fraction. The higher concentrations of Mn, 1 to 2 ppb, occur in the orthoclase- and mafic-rich portions. For the major elements that are important nutrients for plants, Mg, K, and Ca had solubilities between 1 and 6 parts per million (ppm), with the highest concentrations in the finest size fraction or the weathered sample. Na and Si exhibited less solubility at about 0.5 and 0.2 ppm, respectively. The solubility data suggest that this material is relatively benign in terms of release of GSTE to the environment and that, especially in the weathered or finer-sized fractions, may provide useful nutrient elements as a soil amendment.


Bulk concentrations of geoenvironmentally-significant trace elements
(GSTE) in various rock portions of waste fines
10000
1000
100
10
1
Concentration, ppm
Ba
Co
Cr
Cu
Mn
Ni
Pb
Sn
Sr
Th
V
Zn
Bulk, <2mm
Bulk, 2mm-100 mesh
Bulk, 100-200 mesh
Bulk, <200 mesh
Orthoclase-rich
Mafic-rich
Weathered

Oil and Natural Gas Resources of the Wattenberg Field, Denver Basin, Colorado

Debra K. Higley, U.S. Geological Survey, and
Dave O. Cox, Questa Engineering Corporation

Significant quantities of oil and gas have been produced from the Wattenberg field, Denver Basin, Colorado since its discovery in 1970. Cumulative production from all rock formations in the field is listed as 1.5 trillion cubic feet of gas (TCFG), 64.8 million barrels of oil (MMBO), and 12.8 million barrels of water (MMBW) (Petroleum Information Production Data through 1997). More than 779 billion cubic feet of gas (BCFG), 8.4 MMBO, and 6.6 MMBW have been produced from the Cretaceous age D and Muddy (J) Sandstones in the field (Petroleum Information Production Data through 1997). Estimated ultimate recovery (EUR) from current D and Muddy (J) Sandstone wells is more than 1.27 trillion cubic feet of gas (TCFG). Based on production data, estimated field life is greater than 30 years. More than 1,800 gas wells produce from the Muddy (J) Sandstone (Figure 1). Also shown on figure 1 are five major wrench fault zones (WFZ) that were active millions of years ago, and influence present-day reservoir production. The field area is thermally mature for gas generation; source is organic-rich marine shales that bound the D and Muddy (J) Sandstone (Higley and others, 1992).

The Muddy (J) Sandstone was deposited about 97 million years ago in mostly marine and distributary channel (river) depositional environments. These shallow marine, beach, and river sandstones and mudstones were located along the Cretaceous epicontinental seaway, which was an inland ocean that extended from the Gulf of Mexico to the Arctic Ocean. The Muddy (J) Sandstone forms prominent tan-colored sandstone hogbacks that border most of the western boundary of the Denver Basin; it is from these sandstones that most of the oil is produced across the basin. The rocks that comprise the gas reservoir at Wattenberg do not form hogbacks west of the field. They are mostly thin, interbedded mudstones and very-fine-to-fine-grained sandstones that lack the structural integrity to form the ridges.

Average well spacing for D and Muddy (J) Sandstone gas wells (Petroleum Information WHCS data, 1997) is 160 acres. This spacing will probably decrease to 40 acres in some areas of the field. The primary reason for this decrease is to recover a greater percentage of the original gas in place; only about 25 to 33% of the original gas in place is drained by each well. Basically, the sandstone "sponge" cannot be wrung dry. Ultimate recovery from existing wells is about 2 to 2.5 BCFG for each 160 acre tract. Much of the infill would be accomplished by deepening existing wells that are much shallower. Average well spacing is 40 acres for most of the overlying Upper Cretaceous-age Niobrara Limestone, Codell Formation, Hygiene (Shannon) Sandstone, and Terry (Sussex) Sandstone oil and gas production.

The fault zones that were active in the past influence present-day production, as indicated by the highly irregular distribution of gas production across the field (Figure 2). Variation in gas production suggests some faults were sealing, whereas others were open to fluid flow. Vertical offset of faults is minor with the exception of some segments of the wrench fault systems that border and cut the field. Extreme heterogeneity of production in the Wattenberg field results from numerous processes, including vertical and lateral movement along fault zones. The Longmont and Lafayette wrench fault zones bracket the region of greatest gas production. Gas production in the western half of the field extends north and south of these fault zones. The eastern half of the field has limited gas production outside these wrench faults. This may result from sealing behavior that limits lateral migration of gas, leakage of gas along open sections of the faults, and lower permeability of some reservoir intervals. Density of drilling also affects distribution of production. An example is the moratorium on drilling in Greeley, north of the Longmont wrench fault zone; although existing wells here are mostly dry holes (non-productive) because rocks are cemented by silica. The western seal of the field was largely erosional truncation of the primary reservoir interval combined probably with mountain front faulting (Weimer, 1996).

Heterogeneity also results from variation in depositional environments of producing intervals. Increased gas production in the southeast corner of the field results largely from greater porosity and permeability associated with fine-to-medium grained sandstones deposited in a northwest-trending distributary channel system. This is also a primary conduit for gas migration outside the area of source rocks that are thermally mature for gas generation. The Cherry Gulch wrench fault zone, located in this area, did not appear to limit lateral migration of hydrocarbons.

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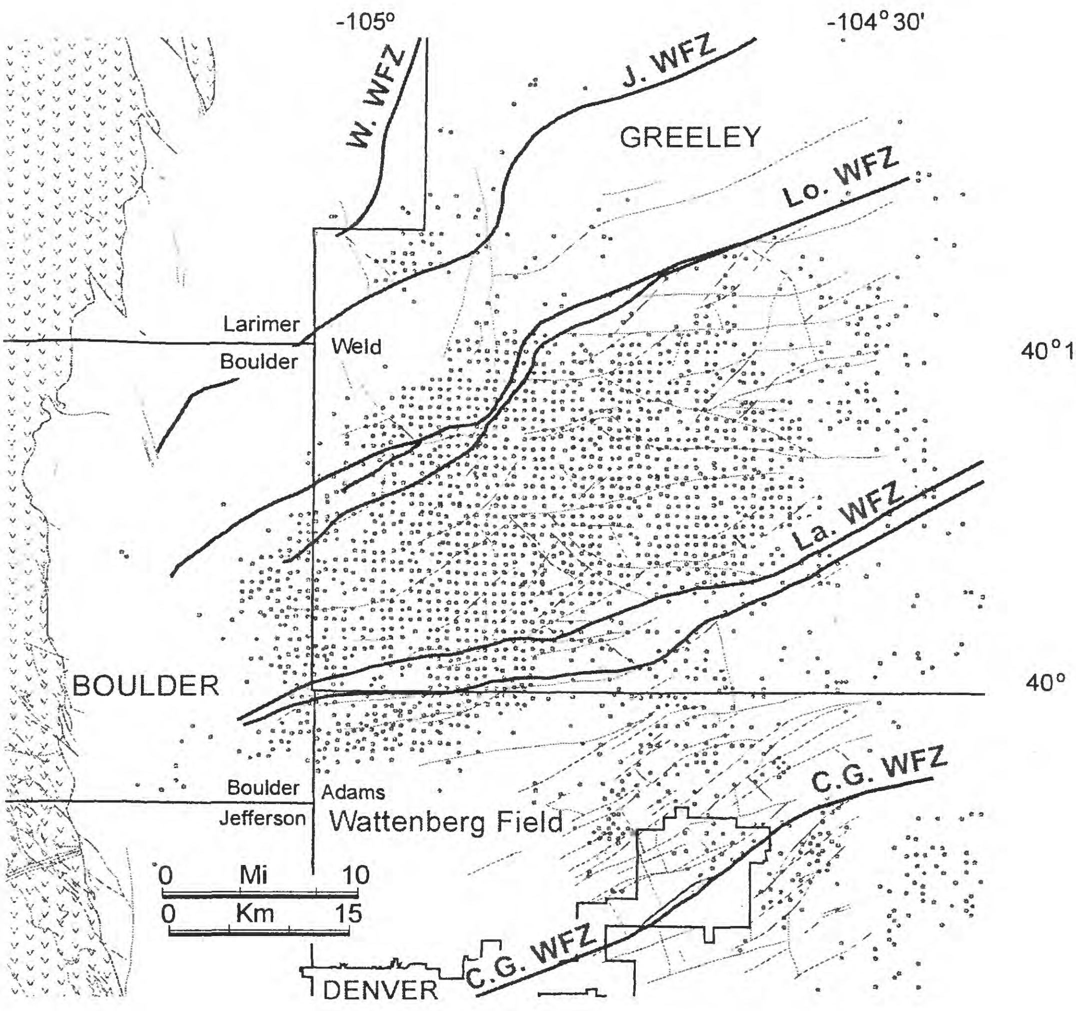

Figure 1. Distribution of gas wells (dots) in the Wattenberg field area, Denver Basin, Colorado. Wrench fault zones (WFZ) (Weimer, 1996) are thick lines. Fault zones are Windsor (W. WFZ), Johnstown (J. WFZ), Longmont (Lo. WFZ), Lafayette (La. WFZ) and Cherry Gulch (C.G. WFZ). Greatest gas production is concentrated between the Longmont WFZ and the Lafayette WFZ. Thin lines delineate faults along the Front Range uplift (V pattern) and hypothetical faults of Weimer (1996) in the field area.

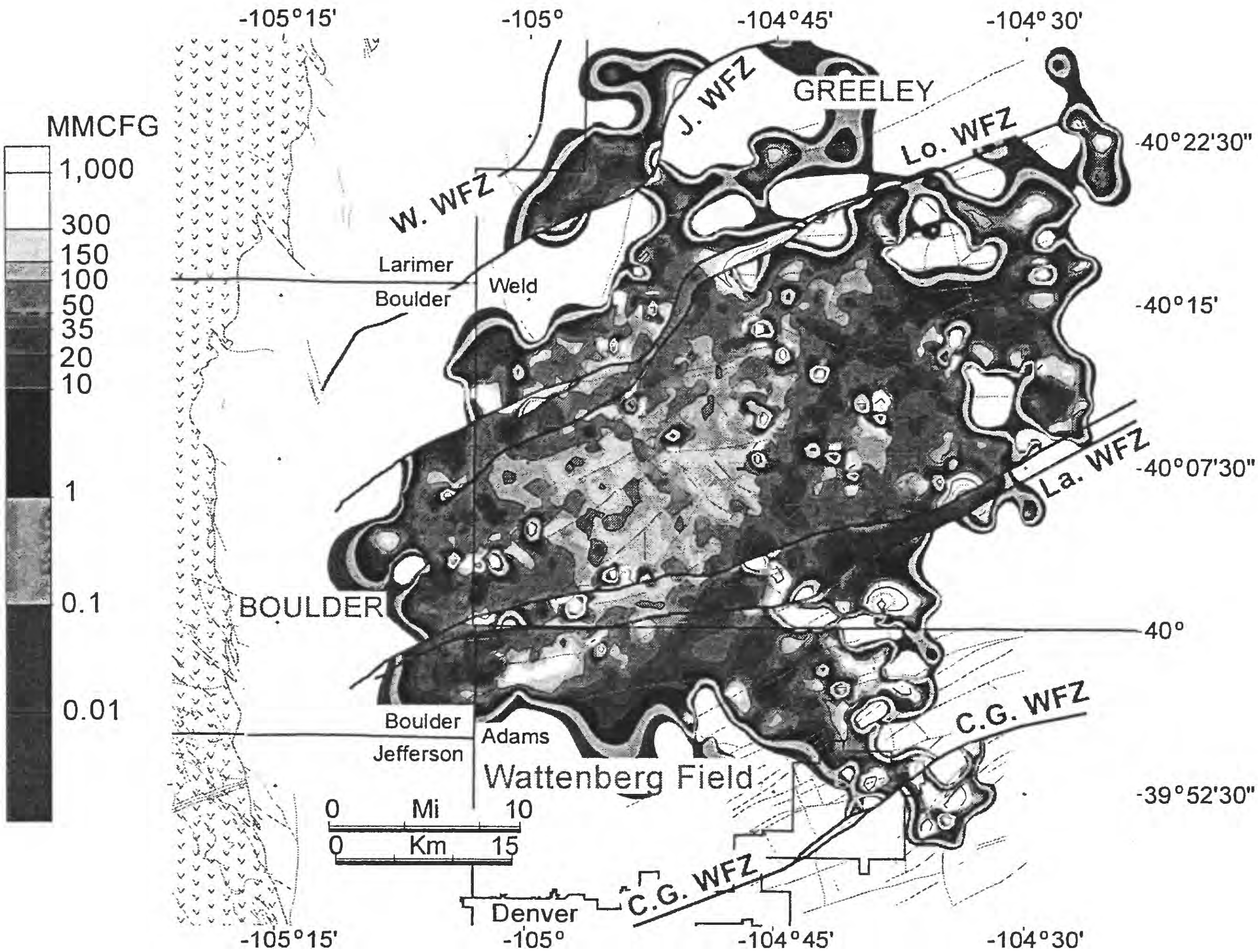

Figure 2. Distribution of the best-12-months of gas production for about 1,800 wells across the Wattenberg field. Greatest production is along a northeast-trending belt proximal to the field and basin syncline. Major wrench fault zones from Weimer (1996) are Windsor (W. WFZ), Johnstown (J. WFZ), Longmont (Lo. WFZ), Lafayette (La. WFZ), and Cherry Gulch (C.G. WFZ). Faults along the Front Range (V pattern) and hypotetical faults within the field (Weimer, 1996) are shown as thin lines.

Aggregate Maps of the Front Range Infrastructure Resources Project Area

William H. Langer, David A. Lindsey, and Daniel H. Knepper, Jr.

Much of the Front Range infrastructure built during the 1950's and 1960's has deteriorated to a point that extensive repair and replacement are required. About half of Colorado highway miles are rated in poor condition. By 2015, traffic is expected to increase more than 50 percent. Rehabilitation and development of new infrastructure requires tremendous amounts of natural aggregate (stone, sand and gravel). During 1995, the Colorado Front Range communities consumed approximately 30,500,000 tons of sand and gravel and 8,000,000 tons of crushed stone, for a total of approximately 38.5 million tons. By the year 2000, aggregate consumption is projected to be approximately 45 million tons per year.

The U.S. Geological Survey recently initiated the Front Range Infrastructure Resources Project. This is a multidisciplinary study along the Rocky Mountain Front Range from Pueblo, Colorado, to Cheyenne, Wyoming, and is designed to collect, compile, and analyze new and existing data on natural aggregate (stone, sand, and gravel), as well as water, and energy resources.

The key to mapping potential sources of aggregate is an understanding of the geology of the region. This includes Quaternary geology for deposits of sand and gravel; stratigraphy, origin, and structural history of the region for crushed stone; and the subsequent weathering or alteration of both sand and gravel deposits or potential sources of bedrock for crushed stone. In order to identify aggregate resources in the Front Range, the 1:500,000-scale digital geologic maps of Colorado and Wyoming were processed to create a reconnaissance map showing locations and quality of both bedrock and surficial sources of natural aggregate in the Front Range urban corridor. Both maps were already available in digital form. These two digital maps were combined and processed into a map showing the distribution and quality of potential sources of aggregate for the Infrastructure Resources Project Area.

Map units were defined as either bedrock or unconsolidated material. Bedrock and unconsolidated materials were each assigned a set of attributes that describes the geologic characteristics of the materials in terms of mode of formation, composition, and texture of each mapped unit. Bedrock was classified according to type (i.e. limestone, granite, gneiss, etc.). Unconsolidated materials were classified according to relative age and weathering characteristics.

The second set of map attributes estimates the physical and chemical properties of each unit for use as aggregate. Physical quality is defined as satisfactory, fair, or poor. Satisfactory aggregate has physical properties that make it suitable for most purposes. It contains clasts that generally are strong, hard, relatively free from fractures, and not chiplike; capillary absorption is very small or absent; and the surface texture is relatively rough. Fair aggregate has physical properties that make it useful for many purposes, but it commonly can not be used where engineering specifications are strict such as in concrete or asphalt. It contains clasts that generally are friable, moderately fractured, and flat or chiplike; capillary absorption is small to moderate; and the surface is relatively smooth and impermeable. Poor aggregate has physical properties that greatly limit its use. It contains clasts that generally are weak, highly fractured; friable; capillary absorption is moderate to high; and the surface is relatively smooth and impermeable. In many circumstances, potential sources of crushed stone can be processed to improve its quality to meet special requirements.

Chemical quality is defined as either innocuous or deleterious. Innocuous aggregate contains no constituents that dissolve or react chemically to a significant extent in the atmosphere, water, or hydrating portland cement, or while enclosed in concrete or mortar under ordinary conditions. Deleterious aggregate contains constituents in significant proportion that are known to react chemically under conditions ordinarily prevailing in portland cement concrete or mortar. The reaction may produce significant volume change, interfere with the normal course of hydration of portland cement, or produce other harmful effects upon concrete.

As an extension of the Front Range project, the entire Colorado Digital Geologic Map is being processed in a manner similar to the Infrastructure Resources Project area. The final product will be a digital map file and supporting database structured so that it can be imported into GIS programs, such as ArcView and Map Professional. All of the descriptive information on the Colorado Geologic Map is contained in the digital database. In addition to descriptive terms for aggregate, the database contains descriptions of geologic units including age, formational names, lithologic description and dominant rock type, mode of formation, and vertical and horizontal variability of the map units.

More detailed digital aggregate maps (1:24,000 scale) have been prepared in collaboration with the Colorado Geological Survey (CGS). Maps from the CGS "Atlas of sand, gravel and quarry aggregate resources, Colorado Front Range Counties," show the distribution of potential resources of sand and gravel and provide general information about the physical properties of the resources. These maps have been digitized and merged into a single Geographic Information System (GIS) database. In addition, the project is adding more specific information to the maps about deposit thickness, volume, and quality. This additional information is being obtained through field characterization studies and modeling activities. The GIS database can be displayed and queried using off-the-shelf software such as ArcInfo, ArcView, and Map Professional. In addition, the USGS is developing a decision support system to assist users in analyzing various land use options on resource availability.

Gravel Deposits of the South Platte River Valley North of Denver, Colorado

David A. Lindsey and William H. Langer

LOCATION, ORIGIN, AND MINING

The South Platte River and its tributaries contain large deposits of gravel used for construction in the Front Range Urban Corridor (Fig. 1). Stream valleys with known or probable commercial deposits of gravel are shown by name on the map. Most other streams lack commercial gravel deposits, although they may contain local occurrences. Commercial gravel was concentrated by glacial meltwater during the Pleistocene ice age. During the ice age, glaciers eroded large quantities of rock from the mountains. Meltwater from glacial ice flooded stream valleys and transported large volumes of gravel down to the plains. Since the last glaciation, about 10,000 years ago, modern streams have reworked some of the gravel, but little new gravel has been brought from the mountains.

The South Platte River north of Denver (study area in Fig. 1) is the last major commercial gravel resource in the Denver metropolitan area (Schwochow, 1980). Most of the deposits upstream in the valleys of the South Platte River, Clear Creek, and Bear Creek have been mined or precluded from mining by urban development. North of Denver, gravel mining has steadily moved downstream since the early 1970's, and now may be approaching the downstream limit of commercial viability. When the deposits north of Denver are exhausted or preempted by other land use, aggregate for the Denver area will by necessity come from stone quarries in the mountains or from gravel deposits in valleys to the north, such as the valley of the St. Vrain River.

The quantity and quality of gravel in the valley of the South Platte River is not only of interest to producers and consumers of gravel aggregate in the area but is also relevant to urban planning. An understanding of the gravel deposits may enable better prediction of the

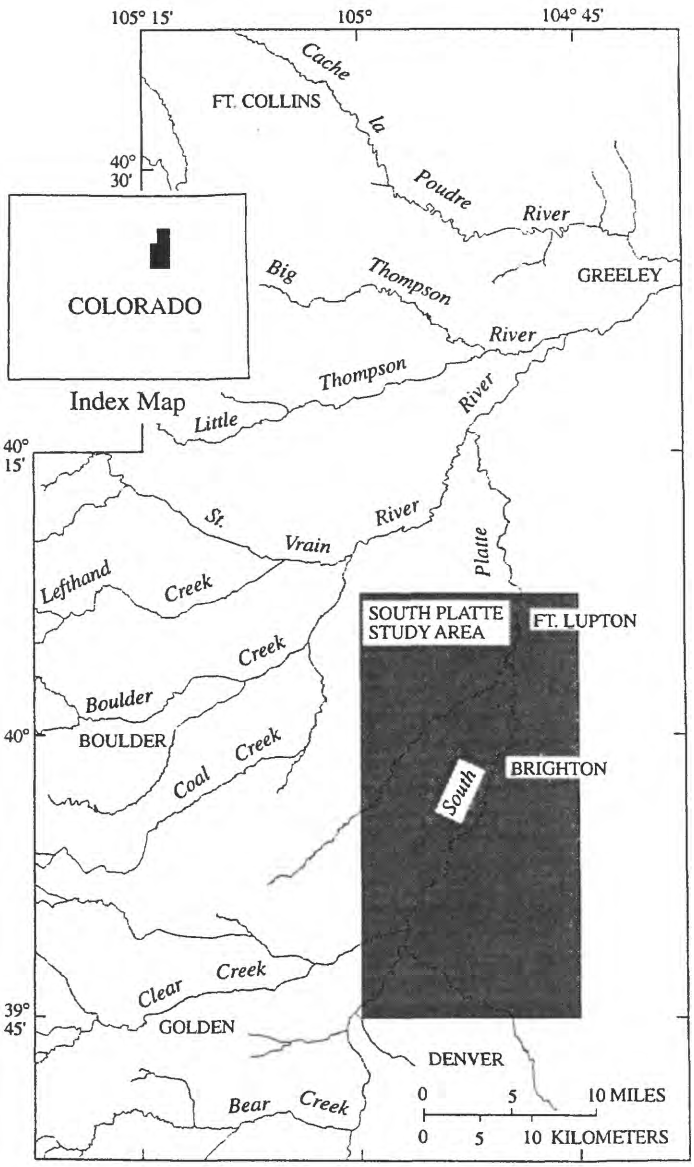

Figure 1.—Map showing the South Platte River and tributary streams north of Denver, Colo. Stream names indicate valleys with major gravel resources or past production. Shaded rectangle is the area of this study.

potential downstream limit of gravel mining and of post-mining land use. To begin to assess the quality and ultimate minable extent of gravel deposits in the South Platte River valley north of Denver, the U. S. Geological Survey conducted detailed studies of the layers and composition of the gravel (Lindsey and others, 1998a,b).

REGIONAL EXTENT OF GRAVEL

The regional extent of gravel deposits in the Front Range Urban Corridor was mapped from aerial photographs and surface studies in the 1970s (Schwochow and others, 1974; Colton, 1978; Trimble and Machette, 1979). The distribution of gravel in the South Platte River valley north of Denver was compiled from these maps.

Gravel underlies multiple terrace levels in the South Platte River valley. From highest (oldest) to lowest (youngest), the terrace levels are remnants of high dissected terraces of Pleistocene age, the high continuous terraces (Louviers and Broadway terraces) of late Pleistocene age, the Piney Creek and post-Piney Creek terraces of Holocene age, and the modern floodplain (Scott, 1965). The Broadway terrace makes up most of the eastern side of the South Platte River valley north of Denver; the low terraces and floodplain occupy the rest of the valley. All of the Holocene levels (Piney Creek, low terraces, and floodplain) are considered together because their gravel resources are similar. Major deposits of gravel underlie the high terraces, but most gravel mining is from the floodplain and low terraces.

VERTICAL EXTENT OF GRAVEL

To map the vertical variation in gravel quality, cross sections (Fig. 2) of the valley fill were prepared from topographic maps, drillhole logs, and observations in gravel pits. The sections show profiles across the valley surface, layers in the valley fill, and the contact between the valley fill and the bedrock that forms the valley floor.

As seen on the section, the South Platte River valley actually consists of three valleys. The largest (and oldest) valley was filled by the high (Broadway) terrace deposits. Gravel beneath the Broadway terrace is covered by a thick deposit of windblown dust. Next in size and age is a valley whose edges are represented by the lower, younger Piney Creek terrace. The Piney Creek valley was formed after the last glaciation. The Piney Creek terrace forms a small step between the Broadway terrace and the lowest surface, which includes the floodplain of the modern river. The smallest (and youngest) valley is the modern valley. The surface of the modern valley consists of the floodplain and very low terraces. The modern valley of the South Platte was formed during the last few thousand years and, indeed, is still forming. The modern valley contains the most valuable gravel deposits, and most gravel mining takes place on it.

The modern valley is underlain by approximately 15-25 feet of gravel. The gravel forms three distinct gravel layers, each about 5-10 feet in thickness. The layers differ in coarseness and color and they can be traced throughout the South Platte valley north of Denver, as far north as Ft. Lupton. Locally, the upper layer contains abundant wood and fossil logjams. Lenses of silty clay, which impede mining, occur locally in the upper and middle layers. The coarse basal layer is crucial to gravel mining because it supplies much of the coarse gravel. The basal layer is thought to be a remnant of gravel deposited in the oldest valley, during the glaciation.

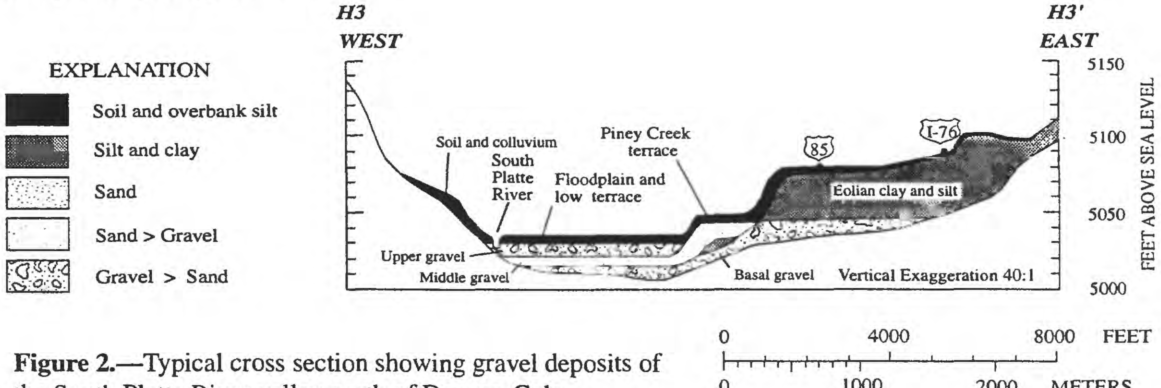

Figure 2.—Typical cross section showing gravel deposits of the South Platte River valley north of Denver, Colo.

Bedrock underlies the alluvial fill of the valley. In the valley north of Denver, bedrock is clay of the Late Cretaceous and Paleocene Denver Formation. The bedrock clay forms an impermeable seal at the bottom of the gravel aquifer, confining ground water flow to the gravel of the river valley. After mining gravel, the pit walls can be lined with clay to create a water-tight reservoir. The reservoir, separated from the gravel aquifer by impermeable clay walls, can be used to store water for municipal use.

GRAVEL PARTICLE SIZE

Particle size of gravel is important to determining the commercial value of a deposit. Coarse gravel yields a higher proportion of aggregate suitable for concrete construction and asphalt paving. Particle size of gravel layers beneath the floodplain and low terraces north of Denver was estimated at three sites in operating gravel pits.

Particle size is determined by sieving carefully selected samples of gravel (Krumbein and Pettijohn, 1938). A vertical trench is first cut in the gravel face. Gravel is then scraped from the trench with a hoe or shovel and collected at the bottom in a bucket or on a tarpaulin. Depending on the coarseness of the gravel, about 30-100 pounds are collected for a sample. Care must be taken to sample evenly across the entire trench. Our studies have shown that much of the variation in estimation of particle size comes from collecting the sample.

After a sample is collected, it is sieved (Fig. 3). Sieves are used to catch the proportion of gravel larger than 1 1/2, 3/4, 3/8, and 3/16 inches. Material that passes through the 3/16 inch sieve is coarse sand or finer. Each size fraction is weighed and expressed as a percentage of the weight of the whole sample. Results are plotted in a variety of ways, the simplest being the bar chart. More elaborate plots and calculations are used to determine statistical measures, such as average particle size, that are used to compare samples.

The three gravel layers north of Denver differ sharply in particle size. The basal gravel is composed of coarse pebble-to-cobble gravel, the middle gravel contains more sand than gravel, and the upper gravel contains variable particle sizes with concentrations of sand. Overall, the upper gravel is coarser-grained than the middle gravel. Taking into account the differences among gravel units, particle size also varies among the three sample sites. Although particle size appears to decrease downstream at the three study sites, it may also vary in other directions across the valley.

Knowing that the three layers differ in particle size, the sections can be used to locate possible downstream limits of commercial production. One possibility for the ultimate downstream limit of production lies north of Ft. Lupton, where the coarse lower gravel layer disappears. Sections downstream from Ft. Lupton show a preponderance of sand in the valley fill.

OTHER INDICATORS OF AGGREGATE QUALITY

A variety of field and laboratory tests are used to assess the quality and suitability of gravel for use as aggregate (Langer and Knepper, 1998; Marek, 1991). Particle composition (rock type), shape, and rounding can be estimated in the field. Commonly, to permit comparison, particles of a specified size fraction, such as pebbles measuring 3/4 to 1 1/2 inches, are selected for study. This size is appropriate because it is in the range commonly used for construction aggregate.

Rock type, or lithology, is an important indicator of durability and of potential problems, such as chemical reactivity with portland cement.

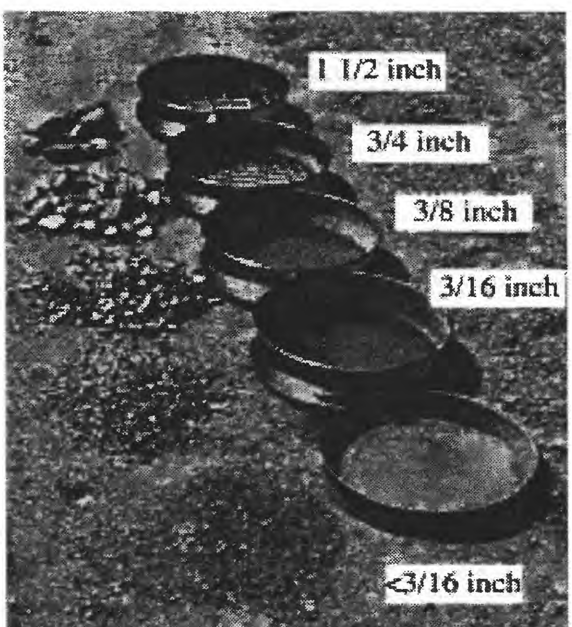

Figure 3.—Photograph showing sieves, size classes, and appearance of gravel in each particle size class.

Gneiss, granite, and pegmatite—all derived from the mountains— make up about 80 percent of the pebble fraction in South Platte gravel and account for the durability of the gravel. Among the minor rocks present, only some of the volcanic porphyries may contain minerals that could cause a chemical reaction with cement. Our study shows that potentially reactive rocks are probably not abundant enough to cause concern.

Particle shape is an indicator of strength. Particles are classified by axial ratios (A=long, B=intermediate, C=short) into equidimensional, disc-shaped, rod-shaped, and blade-shaped. The principal concern is that the proportion of thin, flaky particles (blade-shaped particles with axial ratios below 0.5) not be abundant. Such particles in concrete or asphalt could be potential sites of weakness. Our study shows that, for South Platte gravel, weak particles are not abundant.

Particle roundness is the degree to which particles lack angular corners. Roundness is determined by visual comparison with standards and is classified by letter (A, angular, through E, well-rounded). Possibly, highly rounded particles may not adhere to cement or asphalt matrix, or may shift under load in loose aggregate applications, such as road base, but not much is known about the effect of rounding on aggregate quality. Although our studies show that South Platte gravel is mostly rounded, we know of no problems associated with its use.

In the South Platte valley north of Denver, lithology and shape of the pebble fraction are the same for all three gravel layers. Only minor variation was noted among the three sites studied; rounding differed among the sites.

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Industrial-Mineral Characterization Using Remotely Sensed Data

K. Eric Livo and Daniel H. Knepper, Jr., U.S. Geological Survey, Denver, Colorado

The Front Range Infrastructure Resources Project (FRIRP) is using Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) data and high altitude color-infrared photography to assess the industrial-minerals quality and quantity along the Colorado-Wyoming Front Range Urban Corridor and to characterize surrounding areas. Further investigations will use low altitude AVIRIS flight-data, thermal-infrared (ASTER simulator) data, and interferometry synthetic aperture radar (IFSAR) data. Landsat Thematic Mapper (TM) data are being used for base-maps.

AVIRIS airborne data (Figure 1) is being used to map specific minerals and vegetation within selected sites. The AVIRIS instrument measures the intensity of light reflected from the ground using 224 spectral channels with wavelengths that range from the visible to the near-infra-red. Pixels within the AVIRIS data are processed to identify the most spectrally dominate mineral in the 1 micron and in the 2 micron wavelength regions using USGS software. The method compares selected absorption features within a spectral library to each pixel spectrum and statistically either finds a match or rejects the identification. Similarly, methods which

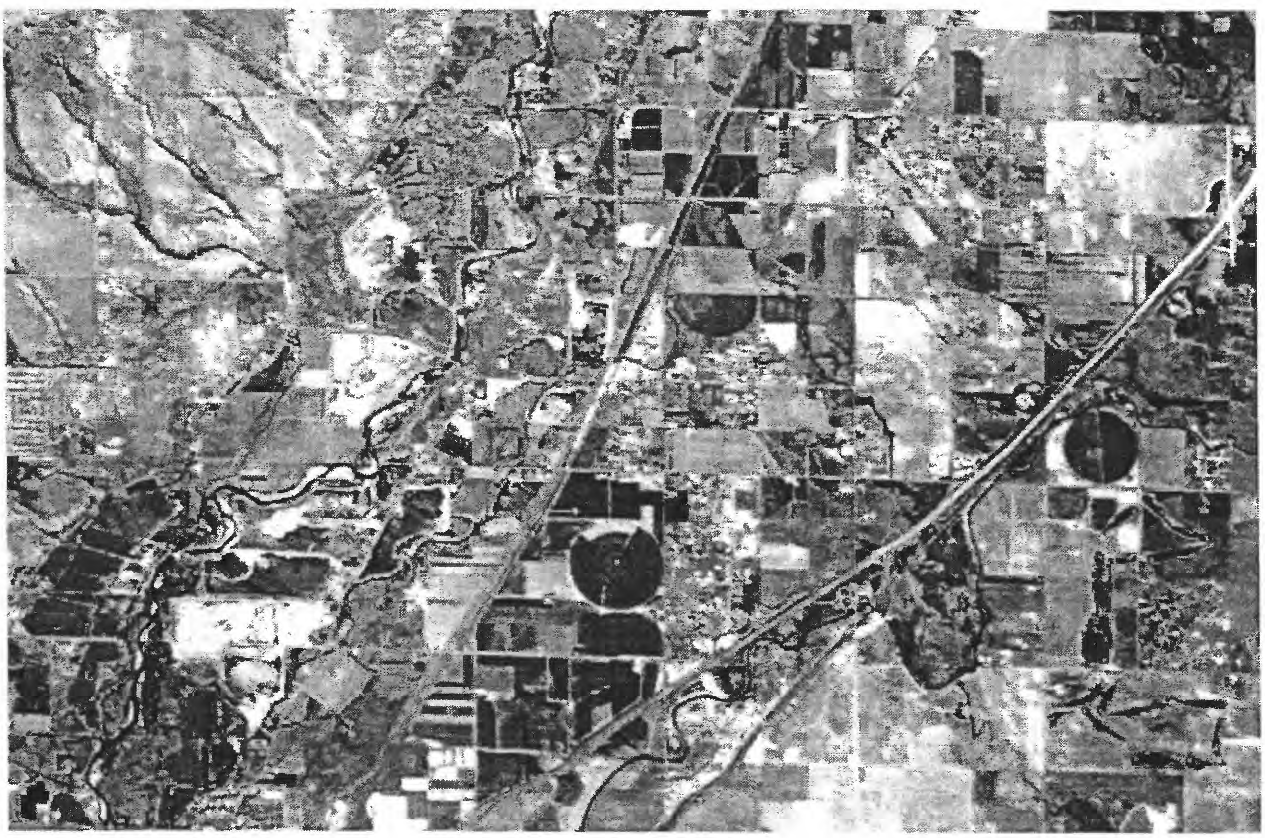

Figure 1 - AVIRIS image of the Platte River southwest of Brighton Colorado
Located in the southwest corner is Western Mobile's Howe sand and gravel pit

classify vegetation are being developed that may yield correlations between vegetation and lithology.

Preliminary study results of the Morrison, Golden, and Commerce City quadrangles covering several clay, sand and gravel, and crushed stone quarries have identified the minerals kaolinite, montmorillonite, hematite, goethite, muscovite, and chlorite, which are minerals either being actively sought, as in the case of clay deposits, or are deposit impurities. A problem so far has been significant vegetation and other ground cover which limits exposure of soils and bedrock. Techniques are being developed in spectral unmixing to subtract these mixed pixel effects.

Several trends appear in the detected mineralogy around Morrison and Golden. Clay within the Morrison Formation and the overlying mined clay beds is classified as kaolinite while some soils around Green Mountain are mapped as containing montmorillionite and smectite. Kaolinite and hematite were detected within the Fountain Formation. Precambrian gneisses used for crushed stone are mapped as having muscovite, hematite, and $Fe+2$ containing minerals and the Ralston Dike has chlorite and $Fe+2$ containing minerals.

Cooperative studies with a university, local governments, the Bureau of Reclamation, and the Biological Resources Division of the USGS are also using the AVIRIS data. The University of Colorado is mapping swelling clays (montmorillonite and smectite) along the plains-mountains interface. Color-infrared photography acquired with the AVIRIS data have been used to map trails by Boulder City Open-Space and structure locations have been identified by the Pine Brooks Hills Fire Protection District. Future vegetation mapping may be used to identify the distribution of invasive weeds and fuel load fire modeling. These investigations may yield techniques which could be applied to infrastructure topics, such as identifying pre-disturbance vegetation communities for reclamation uses.

Future work will include acquisition and analysis of thermal infrared data for classification of the rock-forming minerals feldspar and quartz and low-altitude (high spatial resolution) AVIRIS data for small areal targets. Combining the location of feldspar and quartz with the mapped clays, micas, iron oxides, and other minerals will enable a more precise characterization of the lithology of potential industrial-mineral deposits. Analysis of low-altitude (2 meter spatial resolution) AVIRIS data being acquired this month (October) over Precambrian rock (crushed stone), swelling clay and landslide zones, and sand and gravel deposits may delineate fine mineralogic details within the classified regions and limit mixed pixel effects.

Characteristics and origins of saline (alkalai) soils in the Front Range portion of the western Denver Basin

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INTRODUCTION

Saline (alkalai) soils and wetlands are common in parts of the Front Range Infrastructure Resource Project study area, western Denver Basin. Surface water and shallow groundwater associated with these saline soils and wetlands often exceed 5,000 microsiemens/centimeter (µS/cm) specific conductance compared to a 838 µS/cm northern Front Range regional average (Gaggiani and others, 1987). Areas of saline soils are characterized by poor development of or lack of vegetation, the presence of salt-tolerant plant species, and "white alkalai" salt crusts. In some places, the salt crusts are sufficiently abundant to form small (a few square meters) to locally large (a few hectare) patches of white soils completely barren of vegetation. Such salt crusts are best developed in areas where the water table is within 1 meter of the surface for at least part of the year, typically in the late winter and spring. In other saline areas, patches of barren salt-laced soil are intermingled with patches of soil that support salt-tolerant forbs (weeds). Saline wetlands in the western Denver Basin contain abundant salt-tolerant cattails (*Typhae spp*) and, conversely, are not sites for willow and cottonwood which require relatively fresher water.

Alkalai soils form as salt-rich shallow ground water is transported by capillary action to the surface. The thickness of the capillary fringe is dependent on the texture of the soil or unconsolidated sediment. In coarse, permeable sand the capillary fringe may only be 150 cm thick whereas in less permeable silt and clay it may be 1 meter or more (Henry and others, 1987). Water within the capillary fringe is made more saline by evapotranspiration to the point where the solubility of various minerals is exceeded and the salts precipitate. Although not documented in the Denver Basin, elsewhere such mineral precipitates are often zoned in the soil profile, i.e. the most soluble salts form in the highest part of the profile and the least soluble salts in the lower part of the profile (Timpson and others, 1986). Where the height of the water table is sustained and the supply of salts continues through the summer, thick surface crusts may persist all year. Persistent salt crusts occur in the Front Range study area.

GEOMORPHOLOGY AND GEOLOGY

Detailed mapping of saline soils has been completed in an area extending from the city of Northglenn north to Johnstown then westward to Lonetree Reservoir (lightly shaded area, Fig. 1). Geomorphically, alkalai soils often occur 1) along floodplains of small streams whose drainage basins are entirely underlain by clay-rich Cretaceous and early Tertiary sedimentary rocks of the Denver Basin (for example, Little Dry Creek, Big Dry Creek, and "Indian" Creek (local name), "L", "B", and "I", Fig. 1); 2) on hillslopes underlain by alternating shale, sandstone, and/or thin coal beds; and 3) along shorelines or downvalley from irrigation reservoirs. Alkalai soils are rare along the floodplains of streams and rivers that originate in the crystalline rocks of the Front Range (for example, Coal Creek, Boulder Creek, and St. Vrain Creek, "CC", "BC", "SVC", Fig. 1; darkly shaded area in Fig. 1 is underlain by crystalline rocks) and in drainages underlain by eolian (windblown) sand.

Saline soils form at specific locations on hillslopes. At these locations, shallow groundwater appears to have moved along the gently dipping contact between a thin, water-bearing unit (sandstone or coal bed) and underlying impermeable shale or siltstone. Where these beds intersect the surface topography, ground water moves through the soil to the surface. For example, water contained in shallow coal beds seeps to the surface and forms a linear zone of discontinuous saline soil patches along a hillside parallel to "Indian" Creek in section 23, T2N, R68W. Interbedding of permeable and impermeable beds occurs in portions of the study area underlain by the Denver-Arapahoe Formation, the Laramie-Fox Hills Formation, and the lower part of the Pierre Shale. Mapping suggests that areas underlain by these units tend to have more saline soil patches than areas underlain by eolian sand.

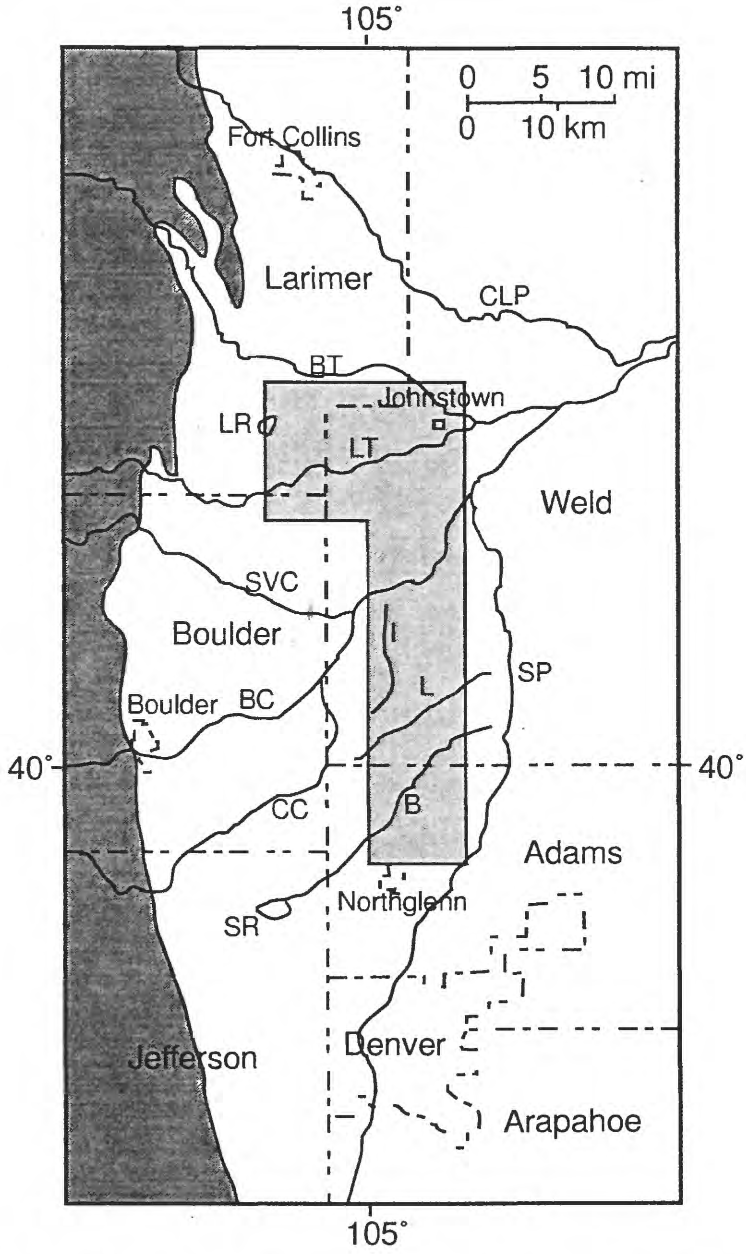

Figure 1- Part of the Front Range Infrastructure Resources Project area showing features related to saline soil development and discussed in text. Lightly shaded area- five 7.5 minute quadrangle area where saline soils have been mapped in detail. Darkly shaded area- area underlain by Precambrian crystalline rocks. CLP- Cache La Poudre River; BT- Big Thompson River; LR- Lonetree Reservoir; LT- Little Thompson River; SVC- St. Vrain Creek; I- "Indian" Creek; L- Little Dry Creek; B- Big Cry Creek; BC- Boulder Creek; CC- Coal Creek; SR- Standley Reservoir; SP- South Platte River.

MINERALOGY AND CHEMISTRY OF NATURAL SALTS AND WATER

Common minerals observed in salt-encrusted soils in the western Denver Basin include thenardite (Na_2SO_4) and mirabilite ($Na_2SO_4 \cdot 10H_2O$), with lesser amounts of gypsum ($CaSO_4$), konyaite ($Na_2Mg(SO_4)_2 \cdot 5H_20$), halite (NaCl), eugsterite ($Na_4Ca(SO_4)_3 \cdot 2H20$), bloedite ($Na_2Mg(SO_4)_2 \cdot 4H_20$), and hexahydrite ($MgSO_4 \cdot 6H20$). Mirabilite samples collected in the field often convert to thenardite through water loss during transport to the lab.

Specific conductance measurements indicate that the surface waters in drainage basins underlain by clay-rich Cretaceous and early Tertiary sedimentary rocks are more conductive, and hence more saline, than surface waters in drainage basins that extend westward to areas in the crystalline rocks of the Front Range (Gaggiani and others, 1987; Otton and Zielinski, 1998, unpublished data). In addition to elevated salinities, high concentrations of sulfate (2100 ppm) have been measured in one of these basins, Big Dry Creek (Gaggiani and others, 1987) which is underlain by clay-rich sedimentary rocks. Aquifers underlying this part of the study area are being recharged with surface waters dominated by sodium and sulfate (Gaggiani and others, 1987).

TECHNOLOGICALLY-ENHANCED SALINE SOILS

Saline soil development appears to be enhanced locally by irrigation and cultivation practices, feedlot runoff, coal mining, road construction, and oil and gas production. Salt crust and saline soil patches often form immediately downslope from irrigation ditches, downvalley from irrigation reservoirs, and at the low end of cultivated fields, particularly those with rows oriented subparallel to the dipslope. In a few drainages, some salts may be contributed by runoff from dairy and cattle feedlot operations. Significant input from such sources as well as fertilizer applications may produce elevated concentrations of nitrate in surface water or sediment leachates. The nitrate concentrations in the waters are not sufficient for nitrate minerals, which are very soluble, to form in saline soils.

Saline soils have also formed in depressions over old collapsed coal mine workings in sec 26, T2N, R68W. The collapse structures may provide a conduit for waters from the former coal mine operations to move closer to the surface. The possibility of such movement is suggested by the limited sulfur isotope data for the sulfate salts at this site. Sulfur isotopes for salts sampled from local coal mine spoil piles in the study area are considerably heavier ($\partial^{34}S$ values ranging from -2 to +5 per mil) than the values of -15 to -2 per mil measured on salts in local soils away from the coal mine sites.

The right-of-way along I-25 in the detailed study area (lightly shaded area, Fig. 1) is a place favored for development of saline soils. Some of these saline soils may have formed where roadcuts intersected shallow water-bearing units. At other locations, alteration of the original topography, compaction of original soils, and addition of fill material may have disturbed the lithology and hydraulic conductivity of soils adjacent to the road berms, thus bringing the water table closer to the surface.

Much of the western Denver Basin has been intensively drilled for natural gas and oil. Saline soils are often spatially associated with oil and gas production facilities throughout the study area. However, only a few salt scar sites of limited areal extent are caused by oilfield produced water seepage from evaporation ponds and water tanks. These soils are characterized by barren soils with minimal salt crusts. Surface water or sediment leachates from these sites contain high chloride concentrations, low sulfate/chloride ratios, and high bromide/chloride ratios compared to soil samples from nearby background sites. The origin of salts at these sites can be determined by (1) careful mapping of the relative position of oilfield water-handling equipment and associated saline soils, (2) discussion with local landowners regarding the history of salt occurrence, and (3) consideration of the geochemical indicators mentioned above. Application of these criteria to several saline soil sites near oil and gas production operations in the Denver basin has indicated that the majority of the salt is naturally derived.

EFFECTS AND MITIGATION

Saline soils limit crop and pasture yields. Over two seasons of observation at selected fields in western Adams and southwestern Weld County, we have noted that germination of spring-planted crops in the salt-affected parts of fields doesn't occur or the plants are stunted depending upon the salt levels. At many field sites, as the growing season progresses the visible surface salt concentrations appear to decrease. This decrease may occur as the seasonal water table drops and rainstorms flush the soluble salts from the root zone. We have observed wind blowing erodable salt from the surface of the field. Salt-tolerant forbs often take over much of the salt-affected parts of the field as the season progresses presumably as the salinity levels drop within their root zone.

Locally, landowners have attempted to mitigate saline soils by installing drainage tile systems beneath affected fields. These systems enhance water movement from the surface into the subsurface by lowering the water table in the field. This allows flushing of salts from the near surface into subsurface drains which carry the salts away from the field. Such systems, however, may be subject to USEPA regulations regarding point discharges to surface waters.

The presence of saline soils is evidence that the water table is close to the land surface. Construction of roads and structures on these sites must allow for persistent wet soil and sodic shrink-swell soils.

CONCLUSIONS

Saline soils affect selected areas of the Front Range urban corridor from the northern Denver suburbs to the Wyoming border. Loss of crop and pasture productivity are the principal effects. The distribution of saline soils is controlled by geology, hydrology, and human activities. The floodplains of streams whose headwaters are in the mountains (Fig. 1, darkly shaded area) are less susceptible to salinity problems probably because the shallow groundwaters are fresher. Floodplains and hillslopes within small drainage basins entirely underlain by the Denver-Arapahoe, Laramie-Fox Hills, or lower part of the Pierre Shale are most likely to contain saline soils. Shallow aquifers in these units appear to carry substantial quantities of salts which are probably largely derived from these bedrock units.

Technologically-enhanced saline soils are generally caused by leakage along irrigation ditches, elevated water tables and leakage adjacent to irrigation reservoirs, ponding of runoff from irrigated fields, and local hydrologic changes near major road rights-of-way. A combination of site mapping and geochemical analyses of salts can be used to identify contribution of salts from water produced along with oil and gas operations. Application of these criteria at several sites determined that produced water from oil and gas production facilities are a very minor contributor to saline soils.

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Digital coverages showing the extent of mining, bedrock faults, and thickness of overburden above abandoned coal mines in the Boulder-Weld coal field, Boulder and Weld counties, Colorado: a cooperative effort by the U.S. Geological Survey and the Colorado Geological Survey

Compilers: Stephen B. Roberts[1] and Jeffrey L. Hynes[2]
Digital compilation: Clark L. Woodward[3]

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In 1996, the U.S. Geological Survey (USGS) initiated the Front Range Infrastructure Resources Project (FRIRP) designed to provide information to land-use planners, decision makers, and the public regarding the location and characteristics of water, aggregate, and energy resources along the Front Range corridor extending from Cheyenne, Wyoming, to Pueblo, Colorado. Within the broader framework of this project, a more restricted demonstration area (fig. 1) encompassing forty-five 1:24,000-scale quadrangles was established as a first step in the implementation of overall project goals. Energy resource issues within the demonstration area relate primarily to (1) the continued exploration and production of oil and gas resources in this heavily populated and growing part of Colorado, (2) the potential environmental impacts of past and present oil and gas production, and (3) the impacts of historic coal-mining, particularly in regard to the potential for subsidence over abandoned mines in recently developed areas or in areas currently being evaluated as residential, commercial, and/or industrial building sites.

In order to address aspects of the abandoned coal mine issue, the USGS and the Colorado Geological Survey (CGS) have jointly undertaken the development of digital map coverages based on previous studies pertaining to the location and distribution of abandoned underground coal mines in the Boulder-Weld coal field north and northwest of Denver. The coal field is located within Boulder and Weld counties, and extends for some 20 to 25 miles from Marshall in the southwestern part of the coal field to areas just north and east of Dacono, Frederick, and Firestone (fig. 1).

Mining began in the coal field during the early 1860's near Marshall (Marvine, 1874; Amuedo and Ivey, 1975), and continued into the 1970's with the last mine closing in 1979 because of fire (Kirkham and Ladwig, 1980). Most of the coal (about 107 million tons) was produced from underground mines, although limited coal was produced from surface (strip) mines during the 1940's and early 1950's.

Digital coverages, based on maps included in a previous coal mine subsidence and land-use study (Amuedo and Ivey, 1975, *after* Lowrie, 1966; Colton and Lowrie, 1973) are being developed by the USGS and CGS that delineate the location and identification of coal mine shafts and adits, the extent of abandoned underground and surface coal mines, the estimated depth of ground cover (overburden) overlying the abandoned underground mines, and the location and orientation of bedrock faults that are present in the Boulder-Weld coal field. To create these digital coverages, base stable (mylar) originals of Amuedo and Ivey (1975) maps showing (1) the extent of mining, and (2) the depth of cover (overburden) above underground mines were used; both of these maps also show the location of mine shafts and adits, as well as the distribution of bedrock faults. Fault locations in Amuedo and Ivey (1975) are based on Colton and Lowrie (1973), and were identified primarily from subsurface records including published coal mine maps, field mapping in abandoned mines, and coal exploration drilling programs. In most areas of the coal field, bedrock faults are not expressed on the surface because of the extensive Quaternary deposits that cover much of the area.

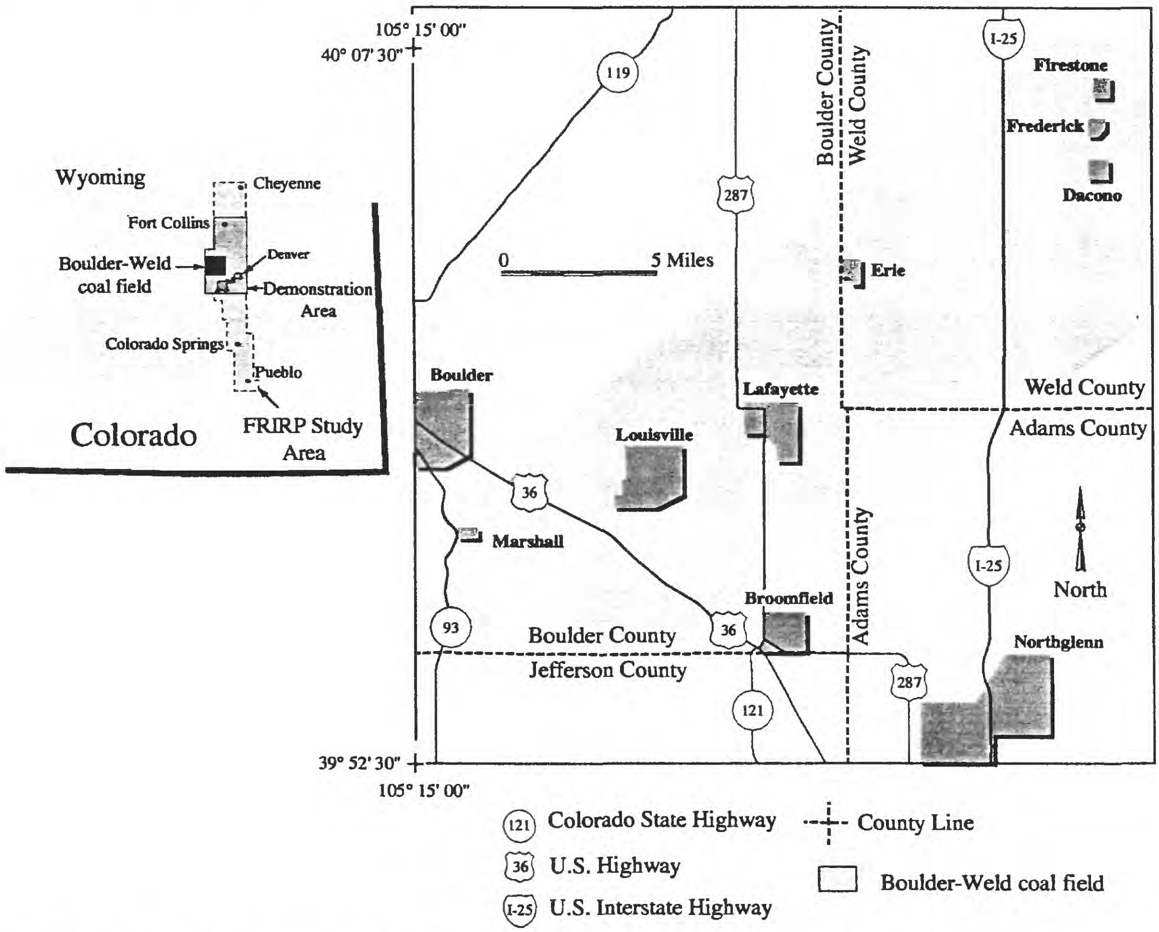

Figure 1: Index map showing the Front Range Infrastructure Resources Project (FRIRP) demonstration area, and the generalized extent of the Boulder-Weld coal field study area in north-central Colorado.

Coal mine data from the original maps (for example, extent, depth, etc.) for each 7.5' quadrangle within the coal field was then photographically reproduced (on base stable mylar), and each quadrangle map was electronically scanned and converted to a Tagged Image File Format (TIFF) image that could be imported into Environmental Systems Research Institute (ESRI) ARC/INFO software[1] for coverage development.

[1] The use of trade names is strictly for descriptive purposes, and does not imply endorsement by U.S. Geological Survey.

Point, line, and polygon coverages were subsequently developed from the "on-screen" digitization of relevant features (for example mine shafts, mine extent, etc.) in the TIFF images for each quadrangle. Through this process, the following 5 composite coverages for all quadrangles within the coal field were created: (1) the extent of abandoned coal mines (polygon coverage), (2) the depth of cover (overburden) above abandoned underground coal mines (polygon coverage), (3) bedrock faults (line coverage), (4) mine shaft (hoisting shaft) locations (point coverage), and (5) rock slope (adit) locations (point coverage).

The coverages developed through this study are intended to provide the basic materials necessary for an initial assessment of lands that are underlain by historic coal mines in rapidly developing urban and commercial areas within Boulder and Weld counties. The availability of these coverages in digital format will provide an opportunity for planners and developers to incorporate these data with other relevant information within computer-based geographic information systems (GIS) as a first step in determining those lands that may require special consideration with regard to development because of the potential for surface subsidence.

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Establishment of Woody Riparian Vegetation at a Former Gravel Pit

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Woody riparian communities provide valuable wildlife habitat, as well as significant human amenities, in arid and semiarid regions of the western United States. The extent and quality of many of these communities have been reduced by a variety of factors, including water development, agricultural conversion, grazing, and invasion by exotics. Extraction of alluvial sand and gravel can also be an important disturbance factor. However, in some situations establishment of native riparian communities may be a viable reclamation alternative for sand and gravel mines.

From 1994 – 1996 we conducted a demonstration project at the WREN Pit in Fort Collins, Colorado, where the objective was to establish plains cottonwood (*Populus deltoides* subsp. *monilifera*), peachleaf willow (*Salix amygdaloides*), and sandbar willow (*S. exigua*) using hydrologic manipulations to provide suitable germination sites during periods of natural seedfall. The WREN Pit is located adjacent to the Cache la Poudre River. The floor of the pit lies below the elevation of the river, and water seeps from the river into the pit. In the southeast corner, a drain culvert equipped with a screw gate extends under the pit wall to a drainage ditch, allowing control of water levels in the pit. Mature, seed-producing cottonwoods and willows occur along the river and the drainage ditch.

Native woody riparian species such as cottonwoods and willows are adapted to germinate on bare, moist, unshaded substrates. Historically, appropriate germination sites were produced by early summer flood flows and the subsequent decline in stream levels, which coincided with the period of natural seedfall. Our basic approach at the WREN Pit was to produce these conditions artificially. Western-Mobile (now Lafarge) prepared the site according to a plan provided by the City of Fort Collins. Site preparation resulted in bare substrate throughout the pit.

We simulated a natural hydrograph by filling the pit with water and conducting a series of annual drawdowns during natural seedfall. We filled the pit in the spring of 1994 using a combination of pumping and natural seepage. We then gradually lowered the water level (about 1 cm/day) while seeds were being produced to provide a fringe of moist soil suitable for germination. In 1995 and 1996, we followed this same procedure, raising the spring water level back to approximately the lowest elevation at which cottonwoods and willows were established in the previous year before initiating the drawdown.

In the spring of 1994 when the water level was at its peak, we measured the perimeter of the pit, including two central islands, at the water's edge. We then randomly selected and marked 67 locations around the perimeter. Following the summer drawdown, we established sampling transects at each of these locations running perpendicular to the water's edge. We marked sampling points every 2 m along each transect and in the fall counted all first-year and older seedlings of plains cottonwood, peachleaf willow, sandbar willow, and saltcedar (*Tamarix* spp., an exotic) within a 0.5-m^{-2} circular plot at each location. We repeated this procedure in 1995 and 1996, in each case extending the transects in their original direction to the new water's edge. In 1966, transects ranged from 4 to 266 m and totaled 1,849 plots. Following seedling counts, we surveyed the location and elevation of plots added each year.

In all 11 species-year combinations (saltcedar did not produce seed in 1996), mean seedling density was significantly higher on plots exposed by the annual drawdowns during the periods of natural seedfall than on plots above the drawdown zones or plots exposed after the periods of seedfall. Frequency of occurrence of seedlings was also highest in the drawdown zones for 9 of 11 species-year combinations. The drawdowns were thus very effective in producing conditions suitable for germination and growth. Reduced seed production by cottonwood in 1994 was reflected in lower establishment, as was the essentially complete failure of the saltcedar seed crop in 1996. Of the 1,746 plots sampled within the total drawdown zone in 1996, 41.1% had at least one individual of one of the native species. Saltcedar was present on only 6.1% of the plots, indicating that simultaneous establishment of this undesirable exotic can be kept to manageable levels.

While judgments about the ultimate success of this project in producing mature trees will not be possible for several years, native woody vegetation is developing well, and we believe that the technique employed has potential application at other sites where water levels can be controlled. In addition, this approach to reclamation may be less expensive that other methods (e.g., pole planting). It also assures use of local genetic material and provides significant habitat for many species (e.g., waterbirds, amphibians) while restoration is in progress.

Mapping and Analyzing the Relationship between Habitat for the Preble's Meadow Jumping Mouse and Aggregate Resources

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Seth McClean and Dave Lovell, Colorado Division of Wildlife

INTRODUCTION

The Preble's meadow jumping mouse (*Zapus hudsonius preblei*) has been listed as a federally threatened species (U.S. Fish and Wildlife Service 1998). This mouse lives primarily in heavily vegetated riparian habitats, and has a distribution restricted to southeastern Wyoming and eastern Colorado along the Front Range. Modification and loss of habitat imperils the continued existence of the mouse. Much of the remaining habitat for the jumping mouse occurs in areas with known or potential aggregate resources (i.e., sand and gravel deposits). There is a need to improve our understanding of the relation between sand and gravel resources and habitat requirements of the Preble's meadow jumping mouse (Armstrong et al. 1997).

PROJECT STATUS

This project involves delineating riparian vegetation within the following (n=25) 7 ½ minute USGS quadrangles:

Lyons, Hygiene, Longmont, Boulder, Niwot, Erie, Eldorado Springs, Louisville, Lafayette, Golden, Arvada, Littleton, Kassler, Sedalia, Devil's Head, Dawson Butte, Castle Rock South, Larkskpur, Greenland, Palmer Lake, Monument, Black Forest, Cascade, Pikeview, and Falcon NW.

The basic method is to use 1:40,000 NAPP infrared aerial photography, photointerpreted according to the riparian habitat classification system. Results are transferred to 1:24,000 mylar and then digitally prepared for input into an Arc/Info GIS.

We are in the early stages of data analyses for the project and must acquire mouse location data for the 1998 field season before we can complete many of the necessary analyses. At this point, we can report on the amount of riparian habitat present in each of several classes of aggregate material. We selected the Littleton quadrangle as an example (Table 1). The data for the Littleton quadrangle indicate that approximately 10% of the total area that contains the highest quality of known aggregate materials (T1 and F1) has some type of riparian vegetation.

Table 1. Aggregate resources and riparian vegetation within the Littleton quadrangle.

Landform Unit/ Resource Class[1]	Total Area (ha)	Amount in each Riparian Vegetation Type		
		Riparian Tree	Riparian Shrub	Riparian Herbaceous
T1	676.53	10.13	17.38	34.80
T3	1208.35	15.92	15.28	2.00
T4	975.73	29.85	22.88	18.15
F1	1109.13	60.03	39.81	10.77
F3	3.48	0.52	0.53	0.04
F4	176.75	7.11	0.56	2.37
E1	2213.93	29.37	5.70	15.58
U2	858.17	4.08	5.31	24.41
U3	74.56	0.00	0.30	0.00
U4	212.53	0.59	0.45	5.25
V4	285.89	59.46	60.99	18.09
Z0	1573.20	1.60	3.56	25.53

[1] Landform units [T = stream terrace deposit; F = floodplain deposit; E = eolian sand (wind deposited); U = upland deposits; V = valley fill (floodplain and/or terrace deposits); Z = not mapped].
Resource class (1 = gravel, relatively clean and sound; 2 = gravel, significant fines, decomposed rock, calcium carbonate; 3 = sand; 4 = probable aggregate resource)

FUTURE TASKS

Data on mouse locations from the 1998 field season must be obtained through the Colorado Natural Heritage Program. Mouse location data from 1998 and previous years will be compiled and compared to the location of sand and gravel resources, as well as riparian habitat resources. An initial question of interest is to determine the relation of aggregate resources to mouse locations and habitat requirements.

An important aspect of this project will be to develop a general rating scheme to identify riparian habitats that are most and least suitable for the jumping mouse. Information on the mouse and its habitat needs will be compiled from published and unpublished literature as well as information furnished by local and regional experts. Mouse location data will be compared to riparian habitat types to determine what relationships exist. The goal is to use this information to identify areas of potential mouse habitat and possibly in further studies of landscape requirements of the mouse. In addition, the maps themselves will provide a strong visual representation of the relationship of the mouse, riparian habitat, and aggregate resources.

This project will be integrated into the USGS's Front Range Infrastructure Resources Project as a specific data layer(s). Potential users of this information include various government agencies and private groups with an interest in the mouse and its habitat.

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