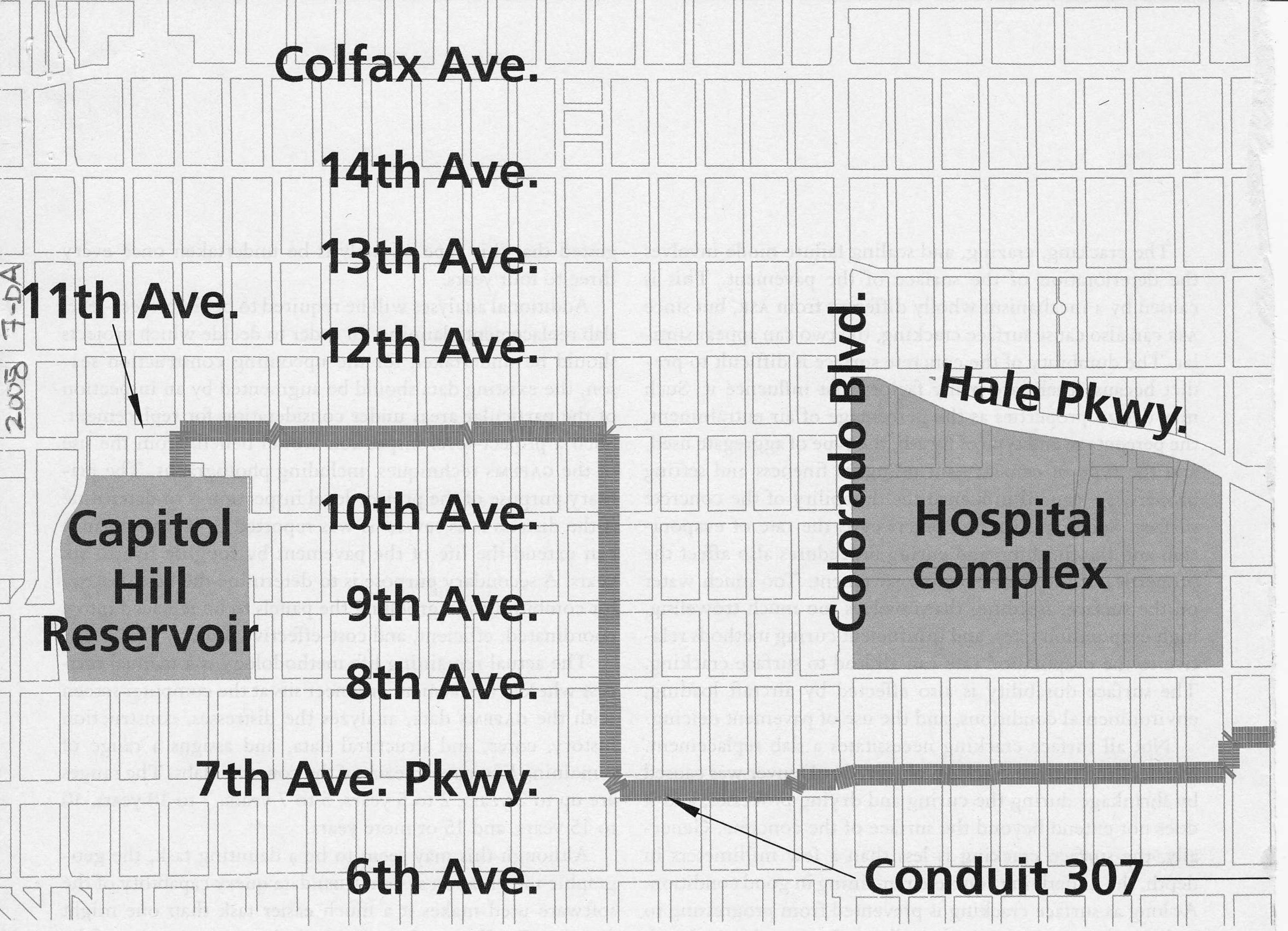
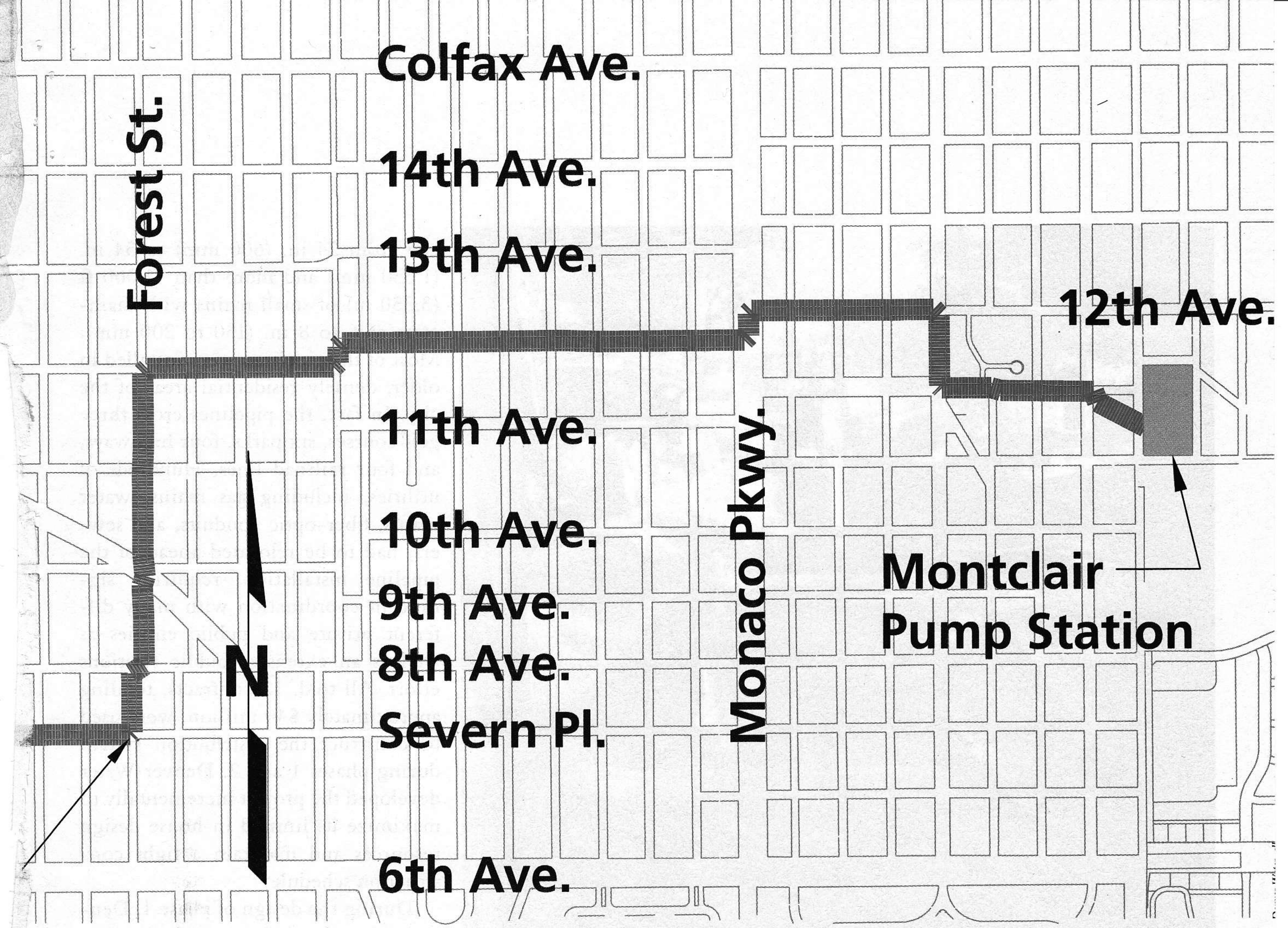


Distributing Denver's Recycled Water

As it seeks to expand its system for distributing recycled water, Denver Water must contend with a host of challenges associated with underground construction in a heavily urbanized environment. As part of its most recently completed phase, the agency constructed a new pump station, a reservoir, and 6.5 mi (10.5 km) of transmission mains. **By Matt S. Turney, P.E.**



To convey recycled water from the 6 million gal (22,710 m³) Capitol Hill Reservoir to the 30 mgd (113,550 m³/d) Montclair Pump Station, Denver Water required an alignment that would avoid a hospital complex, in part because utilities there could not be disrupted. By choosing the 7th Avenue alignment, the utility obviated the need to install pipelines beneath major thoroughfares and avoided a tricky brick storm sewer beneath 12th Street.

With water supplies becoming scarcer, Denver Water views the reuse of water for nonpotable applications as a viable option for helping to meet growing demand, an approach followed in California, Florida, and Arizona. In recent years, Denver Water has begun operating a major water reuse plant, and earlier this year the agency completed a significant expansion of its system for distributing recycled water to users throughout the city. Constructed within urban areas, the pipelines for recycled water required careful attention during design and construction to ensure minimal disruption to neighborhoods, businesses, hospitals, and heavily traveled streets.

Denver Water entered the field of water recycling in part to fulfill its obligations under the so-called Blue River Decree, a 1955 federal court ruling allowing Denver Water to import water from the Blue River, a tributary of the Colorado River located on the western slope of the Continental Divide. The decree also requires that the agency take steps, consistent with legal limitations and economic feasibility, to reuse wastewater so as to reduce or minimize demands on the Blue River. As traditional water supply and storage projects become more difficult and expensive to construct, water recycling has grown in stature.

In 2001 Denver Water began developing a distribution system for recycled water to convey water from a newly constructed treatment plant for recycled water to parks, golf courses, and other large water users in Denver. Effluent from the metropolitan area's major wastewater treatment plant is the source of the recycled water, which undergoes further treatment before it is released for irrigation and other nonpotable uses. The largest plant for recycled water in Colorado, the 30 mgd (113,550 m³/d) treatment facility has been designed so that its capacity can be expanded to 45 mgd (170,325 m³/d). It also includes an 11 million gal (41,635 m³) treated water reservoir on-site and a pump station that can deliver up to 45 mgd (170,325 m³/d) to customers in various pressure zones.

Intended to convey treated water to industrial users and customers that own or operate large expanses of land requiring irrigation, Denver's distribution system for recycled water originally consisted of 13 mi (21 km) of pipelines ranging in diameter from 6 in. (150 mm) to 42 in. (1,050 mm). Referred to collectively as phase 1, the treatment facility and the initial portion of the distribution system became operational in 2004. (See "Denver Opens Water Recycling Plant amid Severe Drought," *Civil Engineering*, June 2004, page 20.)

A 54 in. (1,350 mm) diameter conduit was installed in one of Denver's older residential neighborhoods. Narrow streets and the presence of many utilities and trees made for difficult conditions.

In 2005 Denver Water began designing phase 2 of its distribution system for recycled water. The purpose of this expansion is to convey water for irrigation to portions of two large areas undergoing redevelopment: the land formerly occupied by Stapleton International Airport and the area that was once Lowry Air Force Base. In addition to 6.5 mi (10.5 km) of new piping, phase 2 involves the new, 6 million gal (22,710 m^3) Capitol Hill Reservoir and the 30 mgd (113,550 m^3/d) Montclair Pump Station. Phase 2 became operational this past May.

The distribution piping installed during phases 1 and 2 totals more than 80,000 ft (24,400 m) ranging in diameter from 24 in. (600 mm) to 54 in. (1,350 mm) and more than 11,000 ft (3,350 m) of small mains with diameters of 6 to 8 in. (150 to 200 mm). Most of the pipelines were installed in older, densely residential areas of the city. In fact, the pipelines cross three golf courses, six parks, four highways, and four railroad lines. Hundreds of utilities, including gas mains, water mains, fiber-optic conduits, and sewers, had to be relocated ahead of the pipeline installation, requiring significant coordination with many different private and public entities as well as an extensive public relations effort. All told, 12 contracts, totaling approximately $40 million, were used to construct the distribution system during phases 1 and 2. Denver Water developed the project incrementally to maximize its limited in-house design resources and maintain a tight construction schedule.

During the design of phase 1, Denver Water decided on the basis of its experience not to line the pipes in the distribution system for recycled water with cement mortar based on calcium silicate. The agency has found that the pH of water tends to increase in pipelines lined with such cement mortar, especially at the ends of branch lines and in lines that experience low or intermittent flows. This problem has occurred in the relatively long water mains that branch from Denver Water's main system to serve Denver International Airport. The problem occurs because the transmission mains that deliver water to the airport were constructed larger than necessary in anticipation of future demand. For the moment, the oversized pipelines result in low flows and long travel times. As for the recycled water mains, they are sized for the higher usage that occurs during summer months, so they experience relatively low velocities in the winter.

Leaching of lime from the cement mortar may lead to structural deterioration of the lining and result in an increase in calcium concentrations and the water's pH. In addition to its unpleasant taste, water with a pH above 9.0 can irritate the epidermis as well as internal skin layers

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and the esophagus. Although the reclaimed water is not to be consumed by humans, water with a high pH may harm vegetation. In fact, irrigation water with a high pH can limit the ability of vegetation to take up nutrients. For example, consistently high pH may cause deficiencies of iron or manganese in foliage, resulting in yellowing. Known as chlorosis, this condition ultimately causes leaves and twigs to die.

The pH is more likely to increase in water with low alkalinity. Because rainwater and snow are generally less alkaline than groundwater, this problem is more likely to occur in water distribution systems that are fed from water storage reservoirs that receive their supply from surface runoff, and this is the case with Denver's distribution system. For these reasons Denver Water uses polyurethane and epoxy linings throughout its distribution system for nonpotable water.

Regulation 84, promulgated by the Water Quality Control Commission—a body within the Colorado Department of Public Health and Environment's Water Quality Control Division—governs the use of reclaimed water in Colorado and requires that piping used for reclaimed water be "marked to differentiate reclaimed water from potable water or other piping systems." To comply with this requirement, Denver Water mandated that the recycled water pipeline adhere to the following criteria:

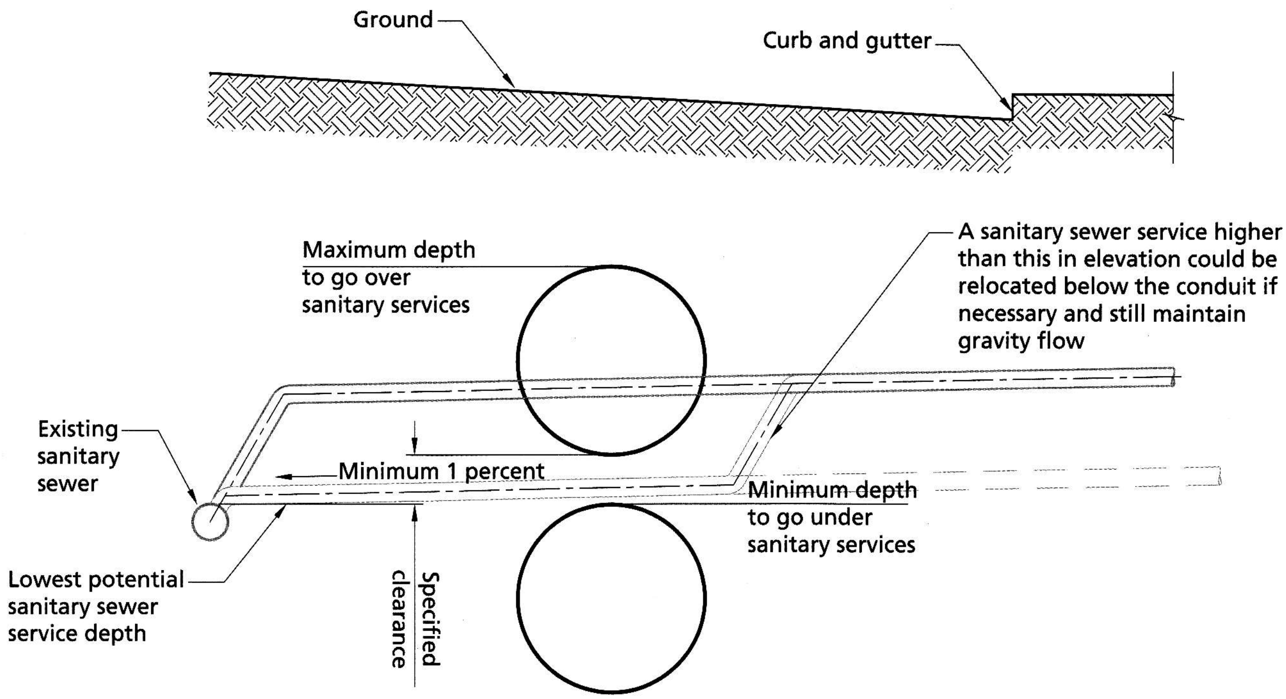
- Purple manhole lids were to be imprinted with the words "Recycled Water" and painted with a purple fusion-bonded epoxy paint.
- Triangular valve boxes, chosen to differentiate them from the potable water system's round valve boxes, were to be imprinted with the words "Recycled Water" and painted with a purple fusion-bonded epoxy paint.
- The pipes were to have a purple exterior. For steel pipe, this meant either a purple tape wrap or a purple polyurethane coating. On ductile iron pipe, purple polyethylene encasement was used. For polyvinyl chloride pipe, colorants were added to the manufacturing compound to give the pipe a purple hue.
- The following warning was to be imprinted along the spring line on both sides of the pipe: Caution: Recycled Water—Do Not Drink. For steel pipe, this warning generally took the form of a vinyl sticker applied in the field. On ductile iron pipe, the warning was imprinted on the polyethylene encasement. For polyvinyl chloride pipe, the warning was imprinted directly on the pipe.
- Warning tape with the same message as above was laid in the trench 1 ft (0.3 m) above the top of pipe.
- Valve nuts were to be purple and pentagonal in shape and were to require special valve keys to be operated.
- Valves within the distribution system for recycled water were required to open in a counterclockwise direction, opposite to the case of the distribution system for potable water.

As mentioned above, in contrast to utilities that are built as development occurs, the pipelines for recycled water had to be constructed within existing infrastructure. In fact, the pipelines were installed throughout densely populated areas of Denver that were developed between 60 and 100 years ago. Conducting a major construction project in an environment of this type entails many challenges relating to heavy traffic, public relations, confined working spaces, and significant interference. The best example of these efforts is the work conducted to design and construct a major segment of the distribution system added as part of phase 2: conduit 307, a pipeline approximately 4 mi (6.4 km) long and 54 in. (1,350 mm) in diameter that conveys treated water from the Capitol Hill Reservoir to the Montclair Pump Station.

The area between the new reservoir and the pump station primarily consists of residential blocks set on a grid and offered hundreds of potential alignments for the conduit. The area's narrow residential streets, which typically are 30 to 36 ft (9.1 to 11 m) wide from curb to curb, offered an obvious solution, as they would obviate the need to construct the pipeline in areas with heavy traffic. Because it would have been very expensive to perform a detailed survey of all of the potential alignments, the alignment was selected on the basis of limited field surveys. Denver Water also relied on maps provided by the various utilities that would be affected to develop a general sense of which alignments might prove optimal.

Two major features in the area further narrowed the list of favorable alignments. The larger of the two is an area encompassing approximately 100 acres (40 ha) that is occupied by three hospitals. Located directly between the proposed reservoir and the pump station, the hospitals essentially form an area off-limits to pipeline construction because there can be

Elevations Showing Sanitary Sewer Service Interference



no disruption of utilities and access for emergency vehicles must be ensured at all times.

The second feature was Colorado Boulevard, which runs perpendicular to the pipeline's route. Used by more than 30,000 vehicles per day, the boulevard is one of Denver's busiest streets. As a result, the pipeline almost certainly would have had to be installed by means of a tunnel under the roadway rather than by using a cut-and-cover method. However, limited locations for tunnel launching and receiving pits presented major obstacles. For example, most of the nearby streets crossing Colorado Boulevard were major thoroughfares themselves, carrying more than 15,000 vehicles per day. Moreover, these streets crossed Colorado Boulevard at an angle.

Placing a tunneling pit in one of these major thoroughfares would have severely disrupted traffic. However, most of the remaining streets were not wide enough to accommodate a tunneling pit at the skewed angle that would have been required to cross Colorado Boulevard. Upon considering these factors, Denver Water selected two crossing locations—12th Avenue and 7th Avenue—for which detailed surveys were to be performed.

The detailed survey of the area around 12th Avenue indicated that an existing 90 in. (2,250 mm) diameter storm sewer would present problems. Made of three courses of bricks, the storm sewer had been installed in the 1930s. Having dealt with a downstream section of this sewer on another project, Denver Water had misgivings about crossing it again. The sewer's elevation was just enough that passing above it would have resulted in inadequate cover over conduit 307. At the same time, the storm sewer's alignment, which traces nearly an S shape, was such that a tunnel passing beneath it in a straight line would have had to cross the sewer twice. Furthermore, an alignment along this path would have run along the northern boundary of the hospital complex. Finally, the crossing at 12th Avenue was not as perpendicular as desired. For these reasons, Denver Water opted to turn its attention to 7th Avenue.

At first, a closer investigation of the 7th Avenue option yielded surprisingly few difficulties. However, to reach 7th Avenue, the conduit would twice have to cross another major street, 8th Avenue. Furthermore, crossing Colorado Boulevard at 7th Avenue would increase the project's total length from an ideal—and fairly straight—alignment of roughly 16,000 ft (4,900 m) to 21,500 ft (6,400 m), adding approximately $2.5 million to the project's total cost. Other factors to be considered were 7th Avenue's designation in the National Register of Historic Places as a historic parkway and the need to protect the 100-year-old elm trees lining the street. Despite these issues, Denver Water selected 7th Avenue as the best location for crossing Colorado Boulevard.

To obtain the additional information needed to complete the design, investigations were conducted to characterize the site's soils and determine the presence and location of other utilities. Crossing at 7th Avenue would require traversing a 48 in. (1,200 mm) diameter storm sewer running down the middle of Colorado Boulevard. Although the sewer itself was not an insurmountable obstacle, the soils investigation revealed that the groundwater table was just below the sewer. The investigation also revealed that the soil exhibited what is called a split-face condition, meaning that two soil types differing with respect to their stability met at the planned tunnel heading.

Since the equipment cost could not be justified for such a short crossing—a mere 140 ft (43 m)—Denver Water opted not to use microtunneling to install the pipeline under the storm sewer. Unfortunately, constructing the 72 in. (1,800 mm) diameter tunnel above the storm sewer would have left only about 4.5 ft (1.4 m) of cover above the tunnel, less than Denver Water wishes to have when tunneling beneath a major active roadway. Deciding that both of these tunneling options posed too great a risk in terms of potential traffic disruptions and might have other consequences, Denver Water approached the construction engineering division within Denver's Department of Public Works to discuss the possibility of constructing the conduit across Colorado Boulevard using opencut methods.

To distinguish them from drinking water and sanitary sewer pipelines, the pipelines for recycled water pipelines, as well as the manhole covers above them, were required to have a purple exterior. Two sides of each pipeline were required to carry the warning Recycled Water—Do Not Drink.

Denver Water and the City of Denver reached an agreement allowing construction crews to install piping within an open trench across Colorado Boulevard during the course of five consecutive nights. According to the agreement, the roadway could be closed to traffic during this period beginning at 10 PM and the surface would have to be paved and reopened to traffic by 6 AM the next morning. Obviously, this arrangement afforded only limited time for installing pipe each night. Furthermore, because of the presence of nearby residences and the requirement that the work occur at night, a sound study had to be performed to establish preexisting noise levels and to monitor sound levels during construction.

The location of sanitary sewers also affected the choice of alignment. Regulation 84 requires that pipelines for recycled water be separated laterally by at least 10 ft (3 m) from sanitary sewers and be at least 1 ft (0.3 m) above sanitary sewers in elevation. However, the sanitary sewers themselves did not present the greatest difficulty. Rather, the obstacles came from the service lines that connected individual residences to the sanitary sewers under certain streets.

Along the pipeline's length, service *(continued on page 86)*

The area between the new reservoir and the pump station primarily consists of gridlike residential blocks and offered hundreds of potential alignments for the conduit. The area's narrow residential streets, which typically are 30 to 36 ft (9.1 to 11 m) wide from curb to curb, provided an obvious solution, as they enabled Denver Water to construct the pipeline in areas with less traffic.

(continued from page 69) lines to homes located west of Forest Street (see figure on pages 64 and 65) feed into sewers that were built in narrow alleys behind the homes. In this case, the service lines would not have to be crossed. East of Forest Street, however, the sanitary sewers were installed within the streets themselves, meaning that the 54 in. (1,350 mm) diameter line for recycled water would have to be constructed below or above the service lines. Because the service lines were typically installed at a depth of approximately 8 ft (2.4 m), the sewers were too shallow to allow the pipeline to be placed above the service lines. As a result, the pipeline would have to be installed beneath the service lines, a costly undertaking.

Generally, approximately 12 service lines were located on one side of a street per block. Although the service lines could be relocated vertically, this approach could be followed only if the proposed elevation of the 54 in. (1,350 mm) diameter pipeline could be accommodated.

Homes in Denver's older sections are generally aligned such that their street access—in other words, their direction toward utilities—is either to the east or the west. Therefore, the problem with the sewer service lines is only an issue when constructing a pipeline with a north–south orientation. Exacerbating the potential conflict with the service lines was the fact that the pipeline had to travel so far to the south—and subsequently back to the north—in order to cross Colorado Boulevard. In the case of conduit 307, this issue could be avoided altogether if, on the east side of Colorado Boulevard, the pipeline resumed its correct northing west of the location where the sanitary sewers begin appearing in the streets rather than in the alleys. This is one reason why Forest Street was chosen for the north–south alignment.

After the alignment selection, utilities were "potholed," meaning that the depths of interfering utilities were obtained. Next, a profile was created to depict the elevation at which the pipeline would be installed. Denver Water then completed the design and sought bids for the project. In February 2006 the agency awarded a $12.5-million contract for the construction of conduit 307 to Arapahoe Utilities and Infrastructure, of Englewood, Colorado. Northwest Pipe Company, of Denver, manufactured steel pipe for the project. In May of that year construction began on the three 72 in. (1,800 mm) diameter tunnels of the conduit 307 project. A month later, two to four crews at a time began laying pipe until the project was complete, in May 2007. Meanwhile, construction of the reservoir was completed in June 2007, and the pump station became operational this past May.

Construction work on the conduit proceeded smoothly, with the exception of a series of snowstorms that dumped more than 30 in. (762 mm) of snow in a three-week period at the end of 2006 and the beginning of 2007. Despite having to halt work because of the inclement weather, construction was completed nearly on schedule and for little additional cost. Overall, change orders increased the project's cost by only 3.2 percent.

The largest component of these changes by far involved the poor existing condition of certain residential streets, some of which had as little as 1.5 in. (38 mm) of asphalt. This layer of existing asphalt meant that the contractor could not remove the top portion of the roadway without digging into the subbase. It also meant that there would not be enough asphalt left on which to apply an overlay after trench construction.

The decision was made to pave these streets curb to curb with 4 in. (100 mm) of asphalt in an effort to leave the streets in a condition better than they were found. Adding asphalt to approximately 10,000 linear ft (3,050 m) of residential street, for a total area of approximately 34,000 sq yd (28,000 m^2), increased the overall contract cost by 2.5 percent. By comparison, all other change orders increased the contract cost by a mere 0.7 percent. This ideal outcome can be attributed to a meticulous survey investigation along the chosen alignment, excellent work by full-time inspection personnel, and a good working relationship with a contractor that was interested in building a relationship with the owner.

Successful pipeline projects require that as much effort be expended to deal with outside forces as to conduct the design itself. Experience has shown that, during a project's design phase, the time spent coordinating efforts with other parties, researching utilities, and communicating with the general public and the proper permitting agencies pays off handsomely in that there are fewer difficulties during construction.

In terms of public relations, Denver Water provided a telephone number that residents could call at any time to voice complaints or ask questions. The agency responded promptly to complaints in an effort to resolve all problems. During the work on Colorado Boulevard, residents within a specified "eligibility zone" were provided with hotel vouchers on nights when construction noise was expected to exceed allowable levels. Flyers were distributed to residences and businesses located along the pipeline alignment to inform them of planned construction activities. Finally, "celebration cards" were sent to residents to notify them when construction was complete.

Continued coordination with various public entities and additional public relations work will be needed to successfully extend the distribution system for recycled water to serve more customers. By 2018, when it is expected to reach its full extent, the system will accommodate additional customers throughout Denver, including the wildlife refuge known as the Rocky Mountain Arsenal and even perhaps Denver International Airport, as well as the surrounding area. Upon completion, Denver's distribution system for recycled water is expected to be able to supply approximately 17,500 acre-ft (21.6 million m^3) of water annually at a cost of approximately $200 million. This amount of recycled water will free enough potable water to serve approximately 35,000 households per year. ■

Matt S. Turney, P.E., is a project engineer in Denver Water's Engineering and Construction Division. This article is based on a paper he presented at Pipelines 2007, a conference sponsored by ASCE and held in Boston in July of last year.

Project Credits
Owner and designer: Denver Water
Contractor: Arapahoe Utilities and Infrastructure, Englewood, Colorado
Pipeline supplier: Northwest Pipe Company, Denver