Geographic Information System-based Pipeline Route Selection Process

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Abstract: The Metropolitan Water District of Salt Lake and Sandy recently began construction of the Point of the Mountain Aqueduct. This 1,524 mm (60 in.) diameter pipeline will convey finished water approximately 9 km (12 mi) through mostly developed areas of two communities. Construction of a large-diameter transmission pipeline through heavily developed cities creates many engineering, construction, and public relations challenges. A geographic information system (GIS)-based route selection process was used to provide a rational basis for narrowing hundreds of potential alternatives into one final alignment corridor. The route selection process was based on construction costs as well as important noncost issues. The use of GIS data and GIS analysis software was critical to the success of this project. The GIS software allowed large amounts of pipeline cost-related data to be collected, stored, and documented for each alignment alternative. It was also used to analyze the network of possible alternatives to quickly determine the optimum route between two points based upon construction costs. This allowed for a logical selection and ranking of alternatives, resulting in one final alignment corridor that was acceptable to all of the stakeholders in the project.

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Introduction

The Metropolitan Water District of Salt Lake and Sandy (MWDSLS) supplies drinking water on a wholesale basis to a population base of approximately 500,000 in Salt Lake City, Sandy City, and other water supply agencies in Salt Lake County, Utah. In 1998 the MWDSLS initiated an update to its master plan because its customer agencies, Salt Lake City and Sandy City, had recently completed master plans that identified their long-term water conveyance and treatment needs from the MWDSLS. Salt Lake City and Sandy City showed a long-term need for more water than the MWDSLS conveyance system could deliver. The 1998 master plan update detailed the necessity for the MWDSLS to provide an additional 3.1 m^3/s (70 mgd) in conveyance and water treatment capacity to provide for the future water requirements of its customers through the year 2025.

To address the future water conveyance needs of the MWDSLS, the Point of the Mountain Aqueduct (POMA) conceptual design project was initiated in 2001. The main objective of the conceptual design was to select a viable pipeline route for the POMA so that finished water could be conveyed from the proposed Point of the Mountain Water Treatment Plant (POMWTP) approximately 9 km (12 mi) to the Little Cottonwood Treatment Plant (LCWTP) and to a number of delivery points in between. The MWDSLS is currently in the construction phase of the POMA and POMWTP projects.

The POMA is a 1,524 mm (60 in.) diameter steel pipeline that will be constructed through highly developed areas of two major cities. The majority of this area consists of residential and commercial development, with very little available open space remaining for new pipeline right-of-way (ROW). The aqueduct will cross railroads, canals, creeks, and parks located between the two plants and will be located within existing narrow rights-of-way, including canals and residential streets. In addition, the pipeline may encounter sensitive seismic areas that include liquefaction zones along the valley floor and the Wasatch Fault zone near the foot of the mountains. The goal of this route selection process was to develop an alignment for the POMA that would minimize impacts to neighboring communities and would be made cost effective to construct by minimizing the length and construction costs of the pipeline.

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Pipeline Route Selection Process

The idea of developing a process to select an optimum pipeline alignment between two points is not new. A number of previous route-selection studies have been conducted for large transmission pipelines similar to the POMA (Ryan 2001; ASCE 1998). While there are some differences in the ways the studies are conducted, the same basic issues are always addressed. These include cost, availability of land, and public concerns in the communities through which the pipelines are aligned.

Route Selection Process Summary

It is understood that the construction of a large-diameter transmission pipeline through heavily developed cities will create many

Table 1. Pipeline Route Selection Process

Level	Description	Remarks
1	Pipeline segment analysis	Included the definition of a study area to contain all possible pipeline routes from POMWTP to LCWTP. All streets and corridors in the study area were considered possible alternatives. Each segment was evaluated based upon its estimated degree of construction difficulty. The result of this analysis was the establishment of the long list of pipeline corridor alternatives.
2	Long-list alternative analysis	Included a cost evaluation of the corridor alternatives, as well as an engineering evaluation of fatal-flaw issues. The highest-ranked alternatives were selected from the long list to create the short list of corridor alternatives.
3	Short-list alternative analysis	Included a conceptual-level hydraulic analysis of each alternative, a noncost evaluation of issues affecting project stakeholders, and a final ranking of the short-list alternatives. The result of this analysis was the selection of the highest-ranked overall alternative as the final alignment corridor.

Note: POMWTP=Point of the Mountain Water Treatment Plant; and LCWTP=Little Cottonwood Treatment Plant.

challenges. There will be many engineering obstacles, environmental issues, construction issues, and general public concerns related to the construction of a pipeline of this size and length. The fundamental objective of this route selection process was to provide a rational basis that could be used to narrow hundreds of potential alternatives down to one final alignment corridor. The route selection process must be justifiable to all stakeholders that may be impacted by the new pipeline, both during construction and in the future of its operation. The logical process by which the alignment was selected was based on construction costs as well as important noncost issues.

A route selection process was established for the POMA based upon the following fundamental concepts:

1. A study area was defined to encompass the entire region through which the pipeline may be located. No area was eliminated based upon preconceived ideas;
2. All possible alignments for the pipeline were considered before eliminating alternatives; and
3. A justifiable method was desired to provide a basis for eliminating alternatives from further consideration. This method was used to establish a logical process for moving from a large number of potential alternatives to the final recommended corridor.

The route selection process was organized into three levels of analysis, starting with all possible alternatives and narrowing them down to a final pipeline corridor. The three levels of analysis with their associated descriptions are summarized in Table 1.

Geographic Information System As A Route Selection Tool

In general, geographic information system (GIS) technology can be thought of as a way to attach information to graphics. A GIS may contain the same lines and symbols as a simple CAD drawing, but GIS allows data to be referenced to each graphical entity. These data are stored in a database, allowing the GIS user to sort and analyze this information in an infinite number of ways. GIS technology is ideally suited for a pipeline route selection study because of the extremely large amount of data that must be managed for a project of this size.

In GIS, each graphical feature is related to a description contained in tables in a database. The collection of GIS data for the POMA route selection process involved a large amount of digital mapping of physical, political, and topological features. Examples of the type of data that were collected in GIS format include

- Physical features such as roads, utilities, and canals;
- Political and demographic features such as city boundaries and land ownership parcels;
- Topologic or elevation data; and
- Other features such as digital aerial photographs and seismic zones.

GIS was used as an engineering tool in this process by allowing the engineer to combine various features in order to evaluate how one feature interacts with the others. For example, the utility map was combined with the POMA alignment map to aid in determining the amount of utility congestion that would be encountered within all segments of the proposed alignment.

Additional features of the GIS software allowed analysis of the entire network of possible segments to quickly determine the optimum route between two points based upon cost, actual length, ease of construction, or any other factor. After each of the alignment alternatives was established, the GIS software was used to compare the length and associated costs of each route to allow a logical ranking of the alternatives and ultimately narrow the study down to one final alignment.

Level 1: Pipeline Segment Analysis

The first level of the pipeline route selection process involved the establishment of a study area and the analysis of all reasonable pipeline segments within this area. The pipeline segment analysis included the following tasks:

1. Define the boundaries of the project study area;
2. Identify all reasonable pipeline segments within this area;
3. Rate the segments with respect to cost, difficulty of construction, utility congestion, and other issues that would impact a decision to locate the POMA within each segment; and
4. Develop a long list of pipeline route alternatives from this network of segments.

The following sections describe each of the tasks involved in the first level of the pipeline route selection process.

Definition of Study Area

The first task in the POMA route selection process was to define a study area that would establish the geographic boundaries of the

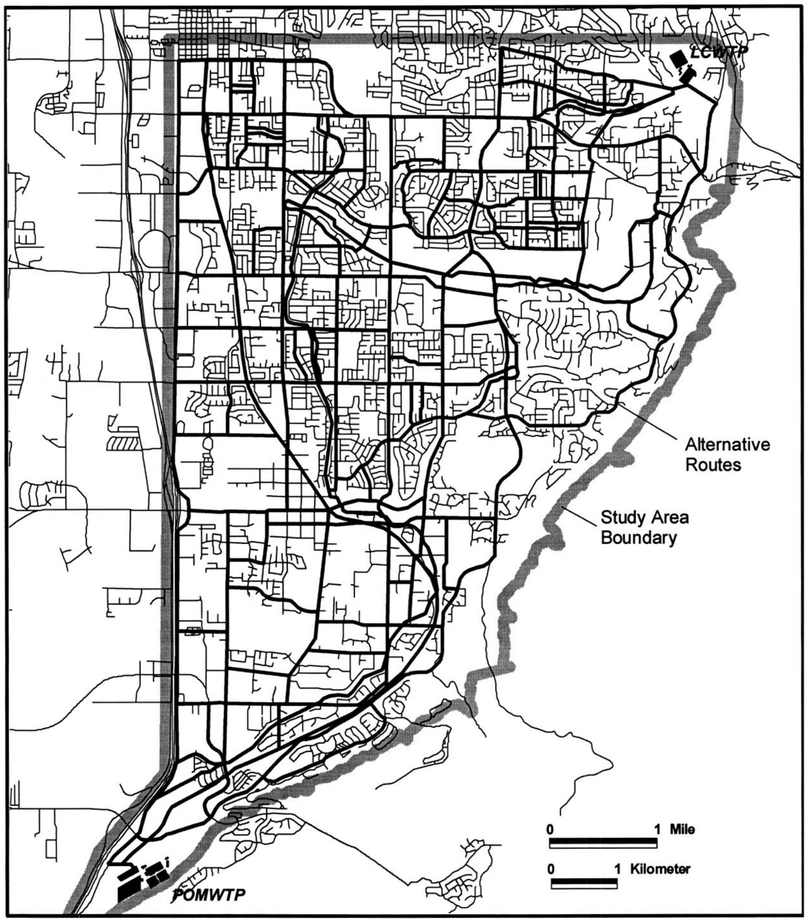

Fig. 1. Pipeline route alternatives for the Point of the Mountain Aqueduct

project. The study area consists of a 78 km^2 (30 mi^2) area that includes physical features from streams and parks to high groundwater areas and active fault zones.

Pipeline Segment Identification

Pipeline segments considered reasonable for the future POMA alignment were identified within the established study area. The segments were identified in conjunction with MWDSLS personnel and input into the GIS. In general, segments included all possible corridors, both public and private, that were free of development. Pipeline segments that were identified for the POMA included public streets, open public and private rights-of-way, railroad corridors, canals, and future road corridors.

The segments were divided to reflect lengths of pipe with similar features to allow each of the segments to be rated properly. Segments were divided each time a change occurred in surface condition or pipeline construction method. A total of 440 route segments were created for the POMA route selection process. These segments included more than 232 km (144 mi) of streets and open rights-of-way. Fig. 1 illustrates the development of the pipeline route alternative segments for the POMA route selection.

Field Investigation

A field investigation was conducted to collect information for each of the 440 pipeline segments. The objective of the field investigation was to identify the physical features that may influence decisions to locate the pipeline within each segment. A standard form was created to assure that the same type of information was collected for each segment and that a standard rating system was used for all the segments. Additional information documented for each segment included general observations, potential public and private disruptions, high groundwater, and environmentally sensitive areas.

Identification of Fatal Flaws

Fatal flaws were identified to eliminate segments that were located in areas determined to be unacceptable for the POMA alignment. The project team identified fatal flaws following review of the physical features of the study area. Segments were considered fatally flawed if their location violated the primary objectives of the project, one of which is to provide a redundant water supply lifeline to the Salt Lake Valley in the event of a seismic event or other emergency.

Utility Investigation

The purpose of the utility investigation was to collect information on all underground utilities that may conflict with the pipeline alignment. Since the presence of underground utilities can significantly affect the cost of pipeline construction, these data were used to aid in the development of conceptual cost data for each pipeline segment.

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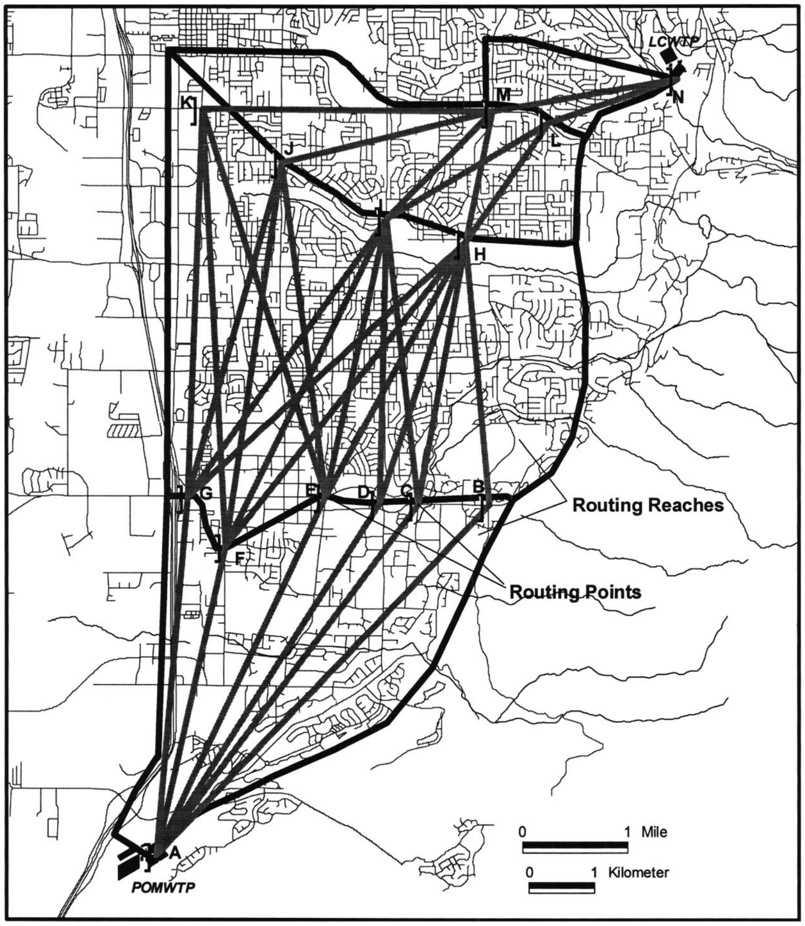

Fig. 2. Routing points and routing reaches

Pipeline Cost Factors

Cost factors were developed for the various pipeline installation conditions observed during the field investigation. Cost information was used for comparison purposes rather than for budgetary numbers in this first level of the route selection process. The objective of this analysis was to provide a method to rank various pipeline routes relative to cost. The cost factors were based upon an average pipeline installation condition that established the factor of 1.0. The unit cost associated with this average condition was estimated using recent pipeline project bid tabulations and construction cost estimates.

Installation conditions determined to be more or less costly than the average condition were assigned factors greater or less than 1.0. Variations from the average pipeline installation condition were categorized as follows:

1. **Urban rating:** Type and traffic congestion associated with street on which pipeline will be constructed;
2. **Utility congestion rating:** Amount of underground utilities that will potentially conflict with pipeline during construction;
3. **Cathodic protection:** Degree of protection pipeline will require if constructed in a corrosive environment;
4. **ROW width:** Available width of pipeline construction area;
5. **Railroad crossings:** Type of railroad crossing (typically jack and bore construction); and
6. **Groundwater:** Existence of high groundwater table in pipeline trench during construction.

The cost factors were used in the GIS model to assign equivalent lengths to each of the pipeline segments. The equivalent length is a cost-weighted length of pipe normalized to the average installation condition. For example, 100 m of pipe jack bored under a railroad (difficult conditions = cost factor of 2.82) may be equivalent in cost to 282 m of pipe installed in a residential street (average conditions = cost factor of 1.00). Equivalent lengths were used to classify each segment according to estimated construction costs of pipeline installation. The combination of segments between two points that generate the shortest equivalent length was considered the least-cost alternative for the pipeline route.

The total cost factor for each segment was calculated by combining each of the six categories listed above. Factors were either added or multiplied together depending upon their relationship to the total cost of the installed pipe. An equivalent length for each segment was calculated by multiplying the total cost factor by the actual length of the segment.

Development of Pipeline Alternatives

Pipeline alternatives were developed following the assignment of equivalent lengths and elimination of fatally flawed segments from the study area. The challenge of creating alternatives from the limitless number of segment combinations required a logical process. It was understood that a list of viable alternatives was required to represent all reasonable corridors available for the POMA within the study area. To accomplish this, the study area was divided into four separate regions, called reaches (or areas defining reaches of pipeline alignment alternatives).

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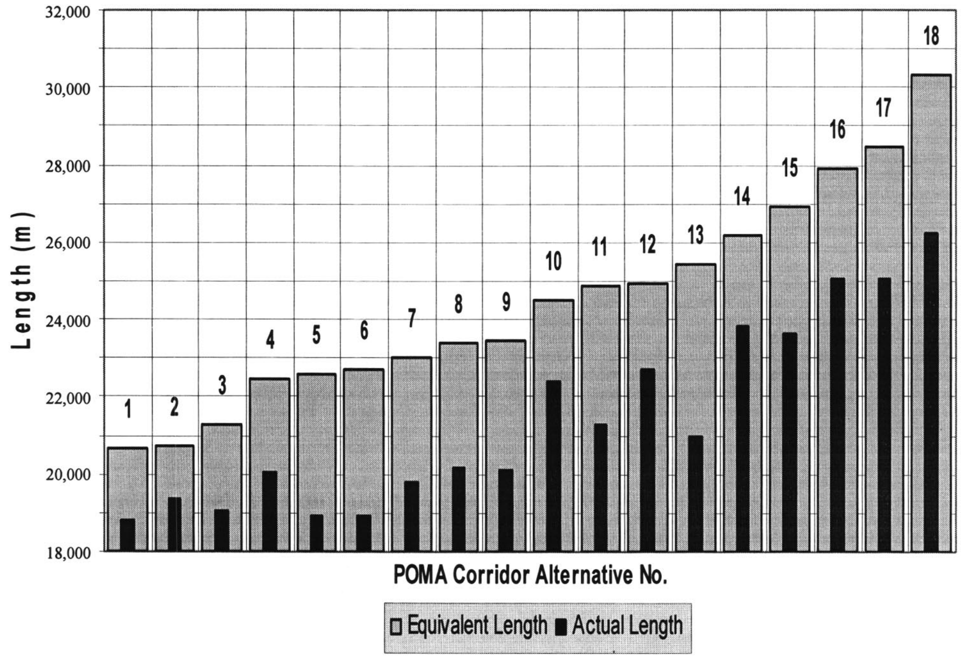

Fig. 3. Actual and equivalent lengths of long-list alternatives

The boundaries between reaches were defined by areas of congested development that appeared to force the pipeline through only a few points along the boundary, which were defined as routing points for the POMA. The routing points between each reach were connected with straight lines to establish the combinations of alternative alignment reaches that were available for POMA.

The routing points allowed the evaluation of each of the shorter alignment reaches between points rather than an evaluation of the full-length pipeline alignment between the two treatment plants. The best alternative reaches between each of the routing points were then joined together to form 28 established combinations to create a hypothetical (or straight-line) long list of alternatives for the POMA. Fig. 2 illustrates the development of routing reaches and routing points for the POMA route selection.

Level 2: Long-List Alternative Analysis

The second level of the route selection process involved the evaluation of these 28 alternatives considering mostly cost issues. The long-list alternative analysis involved the following tasks:

1. Develop long list of pipeline alignments;
2. Rank long-list alternatives relative to cost; and
3. Short list top ranked alignments for further evaluation.

Develop Long List of Pipeline Routes

The 28 pipeline alternative combinations were defined by straight-line connections between the routing points in the first level of the route selection process. The next step was to convert these straight-line combinations into actual pipeline alignments, which were developed using GIS network analysis software. The network analysis software was used to model the least-cost path between each of the established routing points, using all of the cost data (or equivalent lengths) compiled for the 440 segments. The model showed that 10 of the alternative alignments in the long list had redundant paths, so the list was reduced to 18 alternatives. Note that no engineering analysis of the routes had been considered up to this point.

Alternative Evaluation

The objective of the long-list alternative evaluation was to rank each of the alternatives to identify a short list of potential routes for a more detailed evaluation. The purpose was not to identify reasons to eliminate alternatives from the long list, but to select a short list of alternatives for further evaluation. It was understood that the remaining group of long-list alternatives would be considered if the further evaluation of the top alignments revealed hidden flaws in these alternatives.

The alternatives were ranked based upon the equivalent lengths of each route. As stated previously, the pipeline route with the shortest equivalent length was considered the lowest-cost alternative. Fig. 3 provides a summary of the long-list alternatives ranked from shortest to longest equivalent length. The actual length of each of these alternatives is also included in this graph for reference.

Note that the top-ranked alternative based upon equivalent length (least cost) is also the shortest alignment between the two treatment plants. Rankings varied slightly for alternatives located in areas that tended to skew the equivalent length due to higher or lower cost of construction. The fact that the equivalent and actual length rankings are relatively close is evidence that the cost factors were not drastically skewing the results of the analysis.

An evaluation was performed on the ranked list of alternatives. The goal of the evaluation was to develop a short list of approximately five alignments that would satisfy the objectives of the project. The evaluation included a review of cost issues, noncost issues, and engineering-related issues, all of which would be further refined during the short-list alternative evaluation.

Based upon review of these issues, a recommendation was made to short list 5 of the 18 long-list alternatives: numbers 1, 2, 3, 5, and 6. The project team agreed that these 5 alternatives

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required further evaluation because they represented the apparent shortest-length and least-cost routes between the two treatment plants. They also each appeared to satisfy the noncost and general engineering objectives of the project. The remaining 13 alternatives were reserved in case flaws were discovered in any of the 5 short-listed alternatives following further analysis.

Level 3: Short-List Alternative Analysis

The purpose of the short-list alternative analysis was to evaluate each of the alternatives with respect to hydraulic performance, overall cost, noncost issues, and general compatibility with the requirements of the project. The short-list analysis involved the following tasks:

1. Perform a general hydraulic analysis on each of the alternatives;
2. Evaluate alternatives according to cost;
3. Evaluate alternatives according to noncost issues; and
4. Recommend a final alignment corridor for the POMA.

Hydraulic Analysis

A general hydraulic analysis was performed for each of the five short-listed alignments, the purpose of which was to identify the hydraulic differences between the short-list alternatives and also any potentially negative hydraulic aspects of each of the alignment alternatives. The Hazen-Williams formula was used in the hydraulic analysis to estimate head losses, potential gravity-flow capacities, and varying pump sizes for the different pipeline alternatives. The results of the hydraulic analysis indicated that the short list of pipeline alternatives did not vary significantly with respect to hydraulics. Results of this hydraulic analysis confirmed that each of the short-listed alternatives could serve as viable routes for the POMA.

Short-List Cost Evaluation

The five short-listed alternatives were ranked based upon their estimated costs of installation. The costs used in the ranking were based on the pipeline lengths and diameters and pump sizes cal-

Table 2. Noncost Issues Considered for Point of the Mountain Aqueduct (POMA) Route Selection Process

Noncost issue	Description
Constructability	Addresses the ability of the contractor to construct the pipeline in a timely manner without excessive interference from physical obstacles. These physical obstacles could include narrow right-of-way, limited site access, limited staging area, steep terrain/slope, deep trench conditions, or other undesirable surface conditions.
System compatibility	Addresses the requirement for the alternative to perform its proper function in the POMA transmission system. This includes proximity to preferred delivery points, general hydraulic compatibility, and ease of operation and maintenance.
Community disruption	Addresses the impact that the pipeline alternative will have on the local community. This includes the impact during construction on residential areas, commercial access, access to and from public facilities, and emergency services disruption. This category also includes the impacts on the community following pipeline construction.
Traffic and transportation	Addresses the noncost traffic impacts that the pipeline construction may have on the local community. This category includes negative impacts created by limiting access on key roads or disrupting public transportation.
Utility conflicts	Addresses the noncost-related impacts of utility conflicts with the pipeline alignment. This includes the disruption of utility services, lengthy coordination with utility companies, or relocation of utilities and also the possible negative impact of the pipeline on future access to adjacent utilities and utility crossings.
Seismic and geologic considerations	Takes into account the seismic activity around the pipeline corridor, including potential liquefaction zones and fault lines. Other geologic considerations include corrosive soils, rocky conditions, or required special trenching techniques.
Environmental concerns	Addresses the environmental sensitivity of the areas along and around the proposed alignment.
Permit issues	Addresses the possible need for any special permits required by crossing, encroaching, or otherwise impacting the surrounding area.
Right-of-way issues and land use	Addresses the possible need for easement or right-of-way acquisition along the pipeline alignment and possible negative land use changes over the pipeline corridor.

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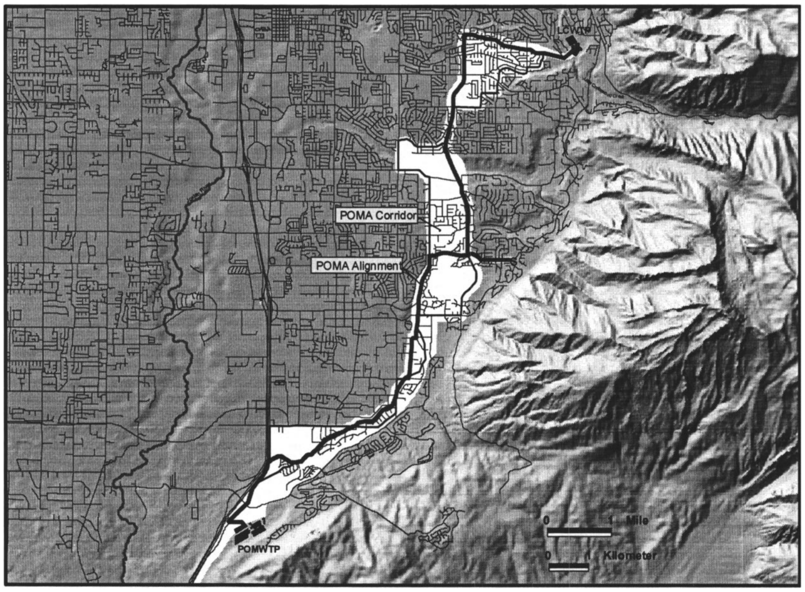

Fig. 4. Point of the Mountain Aqueduct (POMA) final alignment corridor

culated in the hydraulic analysis. Costs for the pipeline alignments were calculated based on the cost factors developed in the first level of the route evaluation process.

Alternatives 1 and 2 were determined to be the lowest-cost routes in terms of overall project hydraulics and pipeline construction. Both alternatives are located within generally open corridors. These two areas are preferred because of the lack of utility congestion and minimal surface improvements associated with these open rights-of-way.

Short-List Noncost Evaluation

The project team understood that a number of issues not related to cost would impact the selection of a final route for the POMA. Construction of the POMA will impact traffic control, disrupt public services, and largely impact adjacent communities and businesses along the entire alignment during construction. There will be permit issues to resolve, environmental concerns to address, and seismic considerations to understand. The location of the aqueduct will impact MWDSLS operations and maintenance staff for the lifetime of the project facilities. Many of these potential problems are not addressed by cost factors alone, making the evaluation of noncost issues an important part of the short-list alternative analysis. Nine categories of noncost issues were identified for the project and are summarized in Table 2.

A survey was created and distributed to each of the project stakeholders following the development of these noncost categories. The project stakeholders included representatives from cities, counties, and agencies that would be impacted by the project. The intent of this survey was to allow the stakeholders to provide critical input during the POMA route selection process.

A rating system was set up for each of the noncost categories. Each pipeline segment in the short list alternatives was rated according to the nine noncost categories. A value of 1 to 5 was assigned to each segment, with 1 being the least and 5 the most favorable. This information was included in the analysis in order to understand the relative importance of the various noncost categories to each alternative. Factors were normalized with respect to the length of each segment so that a very low scoring on a short segment would not skew a higher-scoring longer section. The noncost ratings were developed based upon field investigation data and GIS information such as aerial photographs, zoning maps, seismic zones, canals/streams, hospitals, schools, and parks.

A weighting factor was used to classify each category according to its relative importance in the noncost evaluation. The weighting factors were based on direct input from POMA stakeholders during coordination meetings, and from results of the noncost factor survey that was completed during the long-list evaluation.

According to the results of the noncost scoring, alternatives 2 and 3 were ranked the best according to the noncost issues evaluated. The total noncost scores were very close to the first three alternatives, showing that they are all relatively equal corridors from a noncost standpoint.

Final Pipeline Corridor Recommendation

Results of the short-list alternative evaluation indicated that alternative 2 ranked the best according to cost and alternatives 2 and 3 ranked highest relative to noncost issues. Following a review of the alternatives by the project team, all agreed that each of the top three alternatives would serve as excellent routes for the POMA.

A decision was made to establish a wide final alignment corridor for the POMA that includes the short-list alignments 1 and 2, with variations of alignment 3 included. This corridor includes a recommended alignment with options to allow for flexibility during preliminary and final design. Alignment options were preserved in the final design process to allow for changes that may occur because of utility conflicts, community issues, political pressures, and so on. Fig. 4 illustrates the recommended POMA final alignment corridor.

Conclusion

Final design of the POMA project was completed in October 2004 with only minor changes to the final alignment as recom-

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mended in the route selection process. Construction of the POMA is scheduled to begin in December 2004. The final POMA alignment shown in Fig. 4 has gone through numerous engineering and cost evaluations, community comment periods, and political scrutiny. In nearly all cases, questions regarding the POMA alignment were quickly satisfied after it was understood that a logical and justifiable process was used to arrive at the final location. A route selection process that is well documented, uses the best available data, and allows early input from stake holders will in the end save in design costs and hold up under last-minute criticism. The success of this project was significantly increased by the use of the GIS tools throughout the route selection process. GIS was the tool that facilitated the collection and documentation of critical data used in decision making, but most importantly GIS was used in the analysis of those data to provide the engineer with the solid results required to make the POMA route selection a justifiable and defensible process.

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