OPTIMIZATION AND ANALYSIS OF
CITY OF PANGUITCH
WASTEWATER COLLECTION SYSTEM

A PROJECT PRESENTED TO
DEPARTMENT OF CIVIL AND
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IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE
OF MASTER OF SCIENCE

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This project, by Brian Gant Davis, is accepted in its present form by the Department of Civil and Environmental Engineering of Brigham Young University as satisfying the project requirement for the degree Master of Science.

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EXECUTIVE SUMMARY

For many years, civil engineers have designed wastewater collection systems to convey wastewater (sewage) to the appropriate disposal location. In order to optimize both cost and functionality on such systems many requirements and system specific characteristics must be analyzed. These factors include state law and local codes for the design of wastewater collection systems, topography, soil and groundwater characteristics, flowrate projections and fluctuations, depth of serviceability, hydraulic requirements and a myriad of other factors. Due to the many time and budget constraints placed upon the designing engineer, the optimum design is very difficult and expensive to achieve using standard design approaches.

MODS is a computer program, written by Dr. L. B. Merritt of BYU, designed to aid the optimization of wastewater collection design. MODS optimizes systems using the “dynamic programming” method to find the lowest cost design for new collection systems as constrained by design data and criteria. MODS may be employed to aid the engineer in the planning and preliminary or final design phases.

The City of Panguitch Utah is located in western Garfield County in the southwest portion of the State. Panguitch recently completed installation of a new sewer system. Sunrise Engineering Inc., in Fillmore Utah, completed engineering design for this new system. The MODS program was employed to evaluate this sewer system for optimization of design using data and design criteria provided by Sunrise Engineering Inc. MODS was used to find the most economical design for the original design criteria.
Several parameters used for the design were then varied so that a cost sensitivity for the different parameters could be established. Engineering judgement was employed to decide the limit to which the different parameters could be "massaged" for cost optimization. Alternate designs were presented to find the most economical design for the system with the new design criteria.

This study evaluated an actual sewer system designed by professional engineers in the State of Utah. The study shows how the parameters that most affect the construction costs of new sewer systems can be identified through a cost sensitivity analysis.

Results of these analyses show that MODS can be employed for significant savings in the design of new sewer systems. Savings were demonstrated for the Panguitch wastewater collection system of 3.4% for the same design criteria. The relaxing of certain design criteria, such as minimum velocity and the use of the tractive force model, demonstrated savings of over 15% for this system.

MODS did aid in the optimization of the City of Panguitch Wastewater Collection System. The MODS optimization system has demonstrated itself to be a valuable design tool with significant savings of over 3% and a planning tool with savings of over 15%.
SECTION ONE
INTRODUCTION

1.1 PURPOSE AND SCOPE OF WORK

The purpose of this Study was to analyze current engineering practices in regards to the optimization of the design new wastewater collection facilities. This study specifically examined the recently constructed wastewater collection facilities of the City of Panguitch Utah, located in western Garfield County in the southwest portion of the State. The MODS optimizing sewer design system was employed to establish the most economic design for the system. The MODS design was compared to the actual design performed by Sunrise Engineering Inc. (SEI) in Fillmore Utah.

A range of design variables were then used, so that cost sensitivities for the different parameters could be established. Engineering judgement was employed to decide the limit to which each of the different parameters could be "massaged" for cost optimization. Alternate designs are presented with various design criteria in order to demonstrate the most economical design for the system.

Analyses performed on the Panguitch design allow the approximate dollar cost savings associated with optimization of this wastewater collection system using the MODS program to be quantified. The adjustment of design variables in the design process can also be examined in order to find a set of design criteria that would allow a more cost-effective design with minimal impact to the functionality of the system. The final determination of this study shows the value of optimization-minded engineering of a new wastewater collection system from planning to final design using the MODS program.
1.2 BACKGROUND INFORMATION

For many years civil engineers have designed wastewater collection systems to convey wastewater (sewage) to the appropriate disposal location. In order to optimize both cost and functionality on such systems many requirements and system specific characteristics must be analyzed. These factors include state codes for the design of wastewater collection systems, topography, soil and groundwater characteristics, flowrate fluctuations, depth of serviceability, hydraulic requirements and a myriad of other factors. Due to the many time and budget constraints placed upon the designing engineer, the optimum design is very difficult to achieve using conventional approaches.

Sewer systems are designed to function for many years, often functioning adequately for over a hundred years; therefore, few new systems are designed and most engineers have limited design experience with regard to new sewer systems. Because experience tends to be limited and the service area and population to be served in the future is uncertain, tendencies of over-design predominate in wastewater collection design. Over the years agency guidelines for design have tended to encourage over-design. While over-design generally does not negatively impact the collection system it does in most respects cost more than necessary. This additional cost can provide an unnecessary financial burden on the very people the system was designed to serve.

Historically cost considerations have received limited attention during the design process. The designer reduces what he or she feels possible during the actual design while the more important overall relationships between the selection of design criteria and resultant
costs are not examined. The effectiveness of the actual design process may be improved by employing some type of optimal search, hopefully using the speed of modern computers, thus allowing many more iterations than would be possible for a human designer. Due to the lack of attention to the cost optimization in collection system design process, the most economic design is seldom the design that is taken to the construction phase of the project.

MODS was developed by Dr. LaVere B. Merritt and is owned by Brigham Young University. MODS uses a "discrete dynamic programming" to optimize and is a user-oriented practical sewer design system.

The availability of an optimizing design program such as MODS can provide the design engineer with a tool that will aid in the cost optimization of the design of new wastewater collection systems. MODS promises large savings in design processes employing its optimization procedures in addition to sound engineering judgement. This study employed the MODS program in the analysis of the Panguitch wastewater collection system. These results illustrate the possible savings to be realized by this approach.

The design for the Panguitch City Wastewater Collection and Treatment Facilities project was completed and released for bid February 2, 1996. Schedule A of this design consisted of the collection system for the City. The project has subsequently been bid out and constructed. The contractor was G. W. Johansen of Mt. Pleasant UT. The bid price for schedule A was just over $2,747,000.00 and included mobilization, surface
restoration and all other work for the completion of the collection system. Treatment for
the project was provided in Schedule B, which consisted of a facultative lagoon treatment
system. This system was selected for this study due to the scope of the project, in that an
entire city was receiving the new sewer system as one project, and the cooperative
willingness of Sunrise Engineering in providing the necessary data for the analysis.
SECTION TWO
HYDRAULIC PRINCIPLES OF SEWER DESIGN

Most wastewater collection systems are designed based mainly on regulatory guidelines rather than detailed flow estimates and fundamental hydraulic principles. This situation has developed due to the environment created by the generally over-conservative regulations. In other words, if a design follows the regulatory guidelines, there is a high confidence level that service will be adequate, and since designing for less than the guidelines specify sometimes creates review difficulties with the regulatory agencies, no other design is usually examined. By following standard guidelines, sewer design is reduced to simple calculations for minimum slope and full pipe capacity at specified slopes and distances. This situation creates an environment lacking in technical quality and dulls interest in more economical and more functional systems.

2.1 MANNING’S EQUATION

In Utah and most of the United States regulation for hydraulic design of sewers is based on the Manning equation. The Manning equation is as follows:

\[ Q = \left( \frac{1.49AR^{2/3}S^{1/2}}{n} \right) \]

Where: Q \( (\text{ft}^3/\text{s}) \) is the volumetric flowrate
A \( (\text{ft}^2) \) is the cross sectional flow area
P \( (\text{ft}) \) is the length of the wetted perimeter
R \( (\text{ft}) \) is the hydraulic radius, defined as A/P
S \( (\text{ft/ft}) \) is the slope of the pipe
N \( - \) is Manning’s hydraulic roughness coefficient

The Manning equation was selected as the norm for gravity sewer due to its relative simplicity relative to the more fundamentally accurate Darcy-Weisbach equation.
Modern technology including calculators and computers make the Darcy-Weisbach equation as easy as the Manning equation, but regulations and precedent maintain Manning’s equation as the norm. The inaccuracy of Manning’s equation can be attributed to simplified ‘n’ value or hydraulic roughness coefficient.

2.2 FACTORS AFFECTING ‘n’ VALUES

Calculation of an appropriate ‘n’ value depends on many different variables including temperature, pipe wall roughness, pipe diameter and flow velocity. Applying one ‘n’ value to all situations is an over simplification. The most common ‘n’ value used by the regulatory agencies is 0.013. This ‘n’ value is very conservative and promotes inflated construction costs due to over-design. Manning ‘n’ values significantly lower than 0.013 can be employed in sewer design while maintaining all of the desired functionality of the proposed system. The employment of a lower value for the hydraulic roughness coefficient often results in large cost savings for construction of wastewater collection systems.

There are several variables that affect the ‘n’ value of water flowing through a gravity sewer system, and these variables are not accounted for in standard ‘n’ value assumptions. The exclusion of the affect of these variables causes inaccuracy in standard tables for various ‘n’ values. These inaccuracies lean to the conservative side and may be a source of needless over-design.

The viscosity of water varies with temperature and thus affects the ‘n’ value. A 10°F Change in temperature can cause a change in the ‘n’ value of about 2%.1 This
adjustment of the ‘n’ value is not taken into account in the traditional ‘n’ value approximations. Modern sewer construction materials such as “spun” concrete and PVC have a wall roughness less than 0.0001 ft and merits a lower ‘n’ value than the 0.013 commonly applied to the design of collection systems. The more technically rigorous Darcy-Weisbach equation shows that the ‘n’ value increases with pipe diameter suggesting that the use of a different ‘n’ value for different diameter pipes will provide a more accurate representation of flow through a gravity sewer. The more prevalent smaller pipe diameters should be designed using a lower ‘n’ value in order to provide a more accurate design and greater cost savings due to the flatter slopes required to maintain sewer functionality. The ‘n’ value also decreases as flow velocity increases.

In order to maintain the more favorable flow characteristics described above, good construction and regular sewer maintenance are required, but a lower ‘n’ value than 0.013 more accurately describes the hydraulic roughness coefficient of even substandard conditions. The following table lists recommended ‘n’ values for different diameter collection pipes at different levels of maintenance.

<table>
<thead>
<tr>
<th>Diameter</th>
<th>6”</th>
<th>8”</th>
<th>10”</th>
<th>12”</th>
<th>15”</th>
<th>18”</th>
<th>24”</th>
<th>30”</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extra-care conditions:</td>
<td>0.0086</td>
<td>0.0088</td>
<td>0.0089</td>
<td>0.0090</td>
<td>0.0092</td>
<td>0.0093</td>
<td>0.0095</td>
<td>0.0097</td>
</tr>
<tr>
<td>Common conditions:</td>
<td>0.0099</td>
<td>0.0101</td>
<td>0.0102</td>
<td>0.0103</td>
<td>0.0106</td>
<td>0.0107</td>
<td>0.0109</td>
<td>0.0112</td>
</tr>
<tr>
<td>Substandard conditions:</td>
<td>0.0112</td>
<td>0.0114</td>
<td>0.0116</td>
<td>0.0117</td>
<td>0.0120</td>
<td>0.0121</td>
<td>0.0124</td>
<td>0.0126</td>
</tr>
</tbody>
</table>

These lower ‘n’ values demonstrate that not only is an assumed ‘n’ value of 0.013 too conservative but shows the great benefit that good alignment and regular maintenance can have on the functionality of a system.
Significant cost savings may result from the use of lower ‘n’ values in specific systems. These systems may employ lower ‘n’ value with confidence while realizing a considerable savings.

2.3 SELF CLEANSING VELOCITIES

Sediment build up is a concern in sewer collection system design as it causes a reduction in performance for given pipelines. In order to prevent sediment build up in traditional design the general rule adopted by regulatory agencies is the 2-fps rule. Two feet per second full pipe velocity was agreed upon in an experienced-based consensus using a conservative ‘n’ value of 0.013. The criteria of a flow velocity of 2-fps combined with an ‘n’ value of 0.013 was used to calculate minimum slopes for sewer lines citing the necessary flow rate to prevent sediment build up in the collection pipelines. These conservative slopes can place an unnecessary burden of excessive depths for a system located in an area with flat terrain. In order to avoid the excessive costs to flatter systems, the basis of the minimum slope requirements should be reexamined in light of modern construction principles and understanding of hydraulic principles.

The full pipe method wherein the minimum velocity at full pipe is used to ensure self-cleansing is inexact and full of flaws. For smaller diameter pipes conveying moderate flows this method requires a much steeper slope than the actual slope necessary to assure that the line is capable of self-cleansing and may not require enough slope to do assure self-cleansing in larger pipes. As understanding progresses and technical capabilities increase new methods to assure self-cleansing in sewer pipelines have evolved. The tractive force model provides a more fundamentally sound approach to self-cleansing in
sewer lines. This model assures that a particle with specified size and specific gravity will be sufficiently transported in a pipe with a specified flow and slope. The relationship between these variables is as follows:

$$\tau_c = wRS$$

Where: $$\tau_c$$ is the critical tractive force  
w is the unit weight of water  
R is the hydraulic radius, defined as A/P  
S is the slope of the line

The tractive force model directly calculates the force required to transport the particles in question at a specific design minimum flow rate. The tractive force model does not assume an arbitrary velocity that is a representation of the pipe conditions only when the pipe is flowing full and "seems to have worked fine in the past." The tractive force model provides minimum design slopes that are tailored to prevent sediment build up. For small diameter sewer pipes (6-15") the minimum slopes required by the tractive force model are usually less than the traditional minimum design slopes provided by the regulatory agencies, unless a very small minimum flow is specified. Design slopes depend largely on the flow depth in a pipe at its design minimum flowrate. The minimum slopes derived from the tractive force model are therefore not only derived by a more fundamentally accurate method, but the flatter slopes may also provide great savings in construction cost. The tractive force model should be employed in wastewater collection system design to determine design slopes because it provides a more fundamentally sound and cost effective design. Interestingly, the approach allows flatter minimum slopes for the smaller diameters carrying reasonable design minimum flows, but steeper slopes are required for larger diameter pipes. The cross over point occurs at a diameter of about 18 inches.
2.4 HYDRAULIC CONTINUITY

A wastewater collection system consists of pipes for conveyance of flow and manholes to provide access to the sewer pipelines. Manholes require a drop in grade from one side to the other to prevent sediment buildup and to maintain a constant energy line or "hydraulic continuity" of the wastewater flow. In systems with flatter slopes the velocity through the pipelines is already low the additional strain of a breakup of flow may create sedimentation problems. The break of the hydraulic continuity of a flow is most apparent when combining significant flows in a manhole and in this case appreciable drops through the manhole are usually required. The drop required to maintain hydraulic continuity through the manhole is the same as the calculation of a continuity drop. This equation and the corresponding variables are as follows:

\[
\text{Drop} = (V_2^2 - V_1^2)/2g + (y_2 - y_1) + h_L
\]

Where: \( V_1 \) and \( V_2 \) are the respective upstream and downstream velocities.
\( y_1 \) and \( y_2 \) are the respective flow depths.
\( h_L \) is the headloss through the manhole.

In standard sewer design practices this drop is a constant drop for all manholes (usually 0.10 Feet). This solution to calculating drop through manholes is an over-simplification that is too conservative for most manholes and insufficient for others. The average manhole needs a drop of 0.02-0.05 feet to account for energy losses. A drop through each manhole in a system of 0.10 feet when only 0.02 may be required can add up and force the system much deeper than it needs to be. As in other aspects of sewer design, conservative simplifications of hydraulic principles promote expensive overdesign and is not cost-effective.⁴
2.5 PROJECTED WASTEWATER FLOWS

In the state of Utah the Administrative Rules for Design Requirements for Wastewater Collection, Treatment and Disposal Systems (Appendix A) gives the criteria for projecting wastewater flows for new systems unless the designer wants to present a case for doing otherwise. The basis for design in these rules states that new systems shall be designed for an average per capita flow of 100 gallons per day. These rules further state that laterals and collectors have a peaking factor of 4 and that interceptors and outfall sewers have a peaking factor of 2.5.

A more accurate estimation of flow rates and peaking factors can provide a better description of the flows in a proposed sewer system. Finding a better estimation of probable flows is an important aspect of a sewer collection system design. Accurate estimations of expected flow are necessary for the employment of the tractive force method of calculating minimum slopes for self-cleansing in sewer pipelines. An overestimated flowrate applied to a design may produce a system that does not reach flows sufficient for self-cleansing. Underestimated flows may cause the system to reach capacity before the desired design life.

Estimated wastewater flows may be accurately estimated in most locations by an analysis of winter months culinary water usage and by comparison to nearby serviced areas. Flows estimated in this manner are usually significantly lower than those of the regulating agency's design assumption of 100 gpd per capita, often 70-80 gpd per capita. Peaking factors based upon average design flowrate at a point provide the basis for a
more accurate estimation of design minimum and maximum flow rates.

Peaking factors in modern sewers are found to range from about 4 for design average flows less than about 0.1 cfs to about 2.6 for 1 cfs of flow to 2.1 for flows around 10 cfs. As in other aspects of hydraulic sewer design, a more fundamentally rigorous approach to projecting wastewater flows will not only provide a design soundly based in the fundamental hydraulic principles but often produces a more cost-effective system as well.
SECTION THREE
DESIGN CRITERIA FOR PANGUITCH COLLECTION SYSTEM

3.1 DEMOGRAPHIC DESIGN DATA

Panguitch City Utah is a community dependent upon tourism for much of its business and industry. The population of Panguitch was estimated 1,500 in 1995 when the design for this system was in its beginning phases. At this time 25 motels added to the system a loading tantamount to an additional 108 equivalent residential units (ERU’s). An ERU is a unit equivalent to the amount of flow expected from an average residential hook up. All other government and commercial connections, including restaurants, provides an additional 159 ERU’s. The population of 1500 residents reduces to 594 ERU’s at an average of 2.53 persons per connection. The entire system contains 688 ERU’s that is equal to the flow produced by a population of 2,177 persons in 1995.

The Panguitch City wastewater collection system was designed for a 20-year design life. The design year for this system is 2,016 and equivalent populations for this year will be the basis of design. All residential and commercial connections on 2016 are projected to be equivalent to a population of 2,578 persons.

3.2 DESIGN FLOW RATES

The estimated equivalent population for design year 2016 is 2,578 persons, and at a UDEQ average flowrate of 100 gallons per capita per day this population equates to a total average daily flow of 0.257 million gallons per day (MGD) or 179.02 gallons per minute (gpm). The City of Panguitch will serve a projected 814 connections in the year 2016. The projected flow divided by the projected number of connections yields the
projected flow per connection in the design year 2016. This projected flow in design year 2016 is 0.220 gpm per connection. Other flow rates may be employed in runs of the MODS system; however, this is the design flow mandated by state code for new sewer construction, and was the design flow used in the SEI design.

A second important factor in design flowrates is the peaking factor used to simulate times of peak flow. State code mandated that a peaking factor of 4 be used for collector lines and that a peaking factor of 2.5 be employed for interceptors or transmission lines. The code does not define what constitutes a collector or an interceptor. Due to the relatively small size of Panguitch all lines were defined as collectors and employed a peaking factor of 4 to the average flow in order to calculate a design peak flow. This assumption is probably excessive and in the lower portion of the system and the transmission line to the lift station a peaking factor of 2.5 could have been adapted and been within state code.

3.3 COLLECTION SYSTEM LAYOUT STRATEGIES

Much of the cost in a collection system is decided by the layout of the system. How the manholes are connected and pipeline alignments are laid out. The designer of a system layout must choose the most economical method to serve all of the required connections without laying out extra or unnecessary pipe. In the Panguitch system the layout was strategically placed to collect the east and west sides individually and connect them at one point in order to reduce the amount of borings required under Highway 143 to one. Other strategies such as surface restoration, land acquisition costs and treatment location must also be taken into account for the design of a cost effective collection system layout.
MODS does not change or redesign the planametric layout of the collection system, its optimization is based on the premise that sewer in place costs increase with increasing diameter and depth. While a proper layout is an important part of designing a cost effective wastewater collection system it will not be further examined in this report.

3.4 COLLECTION SYSTEM PIPE SIZING

The pipe sizing calculations for the Panguitch collection system SEI design were based on minimum slope and State code mandated design constraints. These constraints included a minimum velocity in each pipe of 2.0 feet per second (fps) and a Manning’s ‘n’ value of 0.013 with a minimum pipe diameter of 8 inches. The capacity of each size of pipe at minimum slope was then calculated. These capacity calculations were based on Manning’s equation slopes required to assure a minimum velocity of 2.0 fps. The 8 inch diameter sewer pipe could convey a maximum flow of 314 gpm and the 10 inch diameter pipe could convey a maximum of 569 gpm. Upstream connections were then counted at 0.88 gpm per connection (0.220 gpm/connection x peaking factor of 4) to find the flow in a particular pipe. As long as this flow did not exceed 314 gpm an 8 inch pipe was specified if this amount was exceeded then a 10 inch diameter pipe was specified. This is a very straightforward approach based on state code rather than the fundamental hydraulic principles involved.
SECTION FOUR
MODS DESIGN OF PANGUITCH COLLECTION SYSTEM

4.1 INTRODUCTION

In order to test the ability of the MODS program and to compare each MODS design to the actual design used for the Panguitch system, various runs of the program were required. These runs include a number of design options varying certain design constraints. Cost analyses of each MODS run and the original system design were performed to allow for a comparative cost analysis between MODS cost functions and the actual bid construction cost of the project. The design data and constraints for the Panguitch Wastewater Collection System then needed to be input in MODS format, various runs performed and comparisons made pertaining to the original design and the MODS designs of varying criteria. This process allows a selection of the best design alternatives and a cost-basis of comparison for the various designs.

4.2 MODS DESIGN SETUP

In order to have a layout of the Panguitch system and to use the same project criteria as the original design plans of the Panguitch City Wastewater Project were obtained from Sunrise Engineering Inc (SEI).

The plans provided information regarding the location of each manhole within the system and identified each downstream manhole. This information is required by the MODS program to provide the basis for the geometric design of the system. Each manhole was assigned a unique alphanumerical code with which the program identifies that manhole or node. Each node is assigned a surface elevation and a downstream node with
corresponding distance. MODS does not change or redesign the planometric layout of the collection system, its optimization is based on the premise that sewer in place costs increase with increasing diameter and depth. This information is then entered into a text file that provides MODS the information in a format that it can use.

In addition to the geometric layout of the collection system, MODS requires information regarding the hydraulic loading of such a system. This information was set forth in the design criteria portion of the original plans provided by SEI as discussed in the previous section. A specific load was placed upon each manhole with respect to the new load added to the system at that manhole, MODS calculates a running total for the load from all upstream manholes within the system, only the additional loads at each manhole need be specified. The flow per connection was calculated to be 0.88 gpm/connection and the additional flow placed on each manhole consists of the average flow per connection multiplied by the number of connections between that manhole and the next manhole or manholes upstream from the manhole in question. The flow information for each manhole is logged in the text input file that MODS uses for that particular system.

The constraint data for the run must also be designated in the input file for MODS to select the appropriate design constraints for the design run. Default values were established to be the same for the first MODS design as the Utah code and the original SEI design. Those constraints correspond to a Manning’s ‘n’ value of 0.013 and a minimum flow velocity of 2.0 fps. Maximum and minimum depth, maximum velocity and other information can also be placed as system constraints for the various system
runs. The original design did not allow for the tractive force model.

The full original design information from the SEI design is required to allow MODS cost program to compute a cost for the original design to provide a basis of cost comparison between the original design and the various MODS designs. Information regarding invert elevation at each manhole and diameter of pipe for the original system design was required for MODS to build a complete and comparable cost estimate for the original collection system design.

### 4.3 SELECTION OF DESIGN ALTERNATIVES

Various possible designs for the Panguitch system were examined. MODS was first run using the exact same design constraints as the SEI design. Further runs were performed varying the different constraints including minimum pipe diameter, minimum depth, Manning’s ‘n’ values, minimum velocity and the use of a flow multiplier. The use of smaller downstream pipe diameters and the use of the tractive force model were also examined.

A separate set of runs was performed varying each of the different constraints. In this manner the final cost results of varying each individual constraint can be determined and compared. Through a cost sensitivity analysis of these varying parameters, those constraints that have the greatest economic repercussions can be further examined in order to find the cost-effective solution.
4.4 COMPARISON OF DESIGNS

In order to provide a comparison for designs varying a number of constraints, many runs of the MODS program were performed. These runs were organized to show the effects on final design construction cost that result from varying certain design factors. These various runs were logged for comparison of cost and will be further examined in the following section.
SECTION FIVE
DISCUSSION OF RESULTS

5.1 COST SENSITIVITY

Table 5.1.1 shows a summary of the MODS runs for the Panguitch wastewater collection system. Run SEI is the base design attached to the actual construction bid cost of the system as bid by George W. Johansen Construction. A MODS cost analysis was run for the SEI design to provide a calibrating factor that will relate MODS cost functions with actual project dollars for all further runs. The 'MODS' run is the program output for a MODS design with the same design constraints as the original SEI design. Note that given the same design criteria and constraints MODS has demonstrated a possible reduction of construction costs of up to 3.44% for the Panguitch system. All further runs are compared to the MODS run for percent increase in cost for each change in a particular design constraint represented in table 5.1.1 in the column labeled % Increase. The cost of each option was also compared to the original SEI design to compare construction cost savings that may result for each alternative.

Runs A through M varied various constraints including minimum pipe diameter (DmP), minimum depth (Dmin), Manning's 'n' value ('n'), minimum velocity (Vmin) and had a flow multiplier imposed to verify change in final construction costs with change in average flow with a flow multiplier (FM). Run N examined a design where the downstream pipe diameter could be less than the diameter of the upstream pipe, and run O produced a design using the tractive force model. Finally run P examined a possible design changing multiple constraints to view a more cost effective overall design using
the MODS system and adjusted design constraints. This comparison is found in table 5.1.1 in the % Savings column.

Table 5.1.1 Construction Cost of Collection System for Various Constraint Sets

<table>
<thead>
<tr>
<th>RUN</th>
<th>DmP</th>
<th>Dmin</th>
<th>'n'</th>
<th>Vmin</th>
<th>FM</th>
<th>Other Constraints</th>
<th>Cost</th>
<th>Incremental Cost</th>
<th>% Change</th>
<th>% Saving</th>
</tr>
</thead>
<tbody>
<tr>
<td>SEI</td>
<td>8</td>
<td>8</td>
<td>0.013</td>
<td>2.00</td>
<td>1.00</td>
<td></td>
<td>$2,747,400.00</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MODS</td>
<td>8</td>
<td>8</td>
<td>0.011</td>
<td>2.00</td>
<td>1.00</td>
<td></td>
<td>$2,652,800.00</td>
<td></td>
<td>0.00%</td>
<td>3.44%</td>
</tr>
<tr>
<td>A</td>
<td>6</td>
<td>8</td>
<td>0.013</td>
<td>2.00</td>
<td>1.00</td>
<td></td>
<td>$2,526,100.00</td>
<td>$126,700.00</td>
<td>-5.02%</td>
<td>8.05%</td>
</tr>
<tr>
<td>B</td>
<td>8</td>
<td>8</td>
<td>0.012</td>
<td>2.00</td>
<td>1.00</td>
<td></td>
<td>$2,612,600.00</td>
<td>$40,200.00</td>
<td>-1.54%</td>
<td>4.91%</td>
</tr>
<tr>
<td>C</td>
<td>8</td>
<td>8</td>
<td>0.014</td>
<td>2.00</td>
<td>1.00</td>
<td></td>
<td>$2,709,300.00</td>
<td>$56,700.00</td>
<td>2.09%</td>
<td>1.38%</td>
</tr>
<tr>
<td>D</td>
<td>8</td>
<td>6</td>
<td>0.013</td>
<td>2.00</td>
<td>1.00</td>
<td></td>
<td>$2,557,600.00</td>
<td>$95,200.00</td>
<td>-3.72%</td>
<td>6.91%</td>
</tr>
<tr>
<td>E</td>
<td>8</td>
<td>7</td>
<td>0.013</td>
<td>2.00</td>
<td>1.00</td>
<td></td>
<td>$2,602,100.00</td>
<td>$50,700.00</td>
<td>-1.95%</td>
<td>5.29%</td>
</tr>
<tr>
<td>F</td>
<td>8</td>
<td>9</td>
<td>0.013</td>
<td>2.00</td>
<td>1.00</td>
<td></td>
<td>$2,708,100.00</td>
<td>$55,300.00</td>
<td>2.04%</td>
<td>1.43%</td>
</tr>
<tr>
<td>G</td>
<td>8</td>
<td>8</td>
<td>0.013</td>
<td>1.50</td>
<td>1.00</td>
<td></td>
<td>$2,558,800.00</td>
<td>$94,000.00</td>
<td>-3.67%</td>
<td>6.86%</td>
</tr>
<tr>
<td>H</td>
<td>8</td>
<td>8</td>
<td>0.013</td>
<td>1.75</td>
<td>1.00</td>
<td></td>
<td>$2,592,100.00</td>
<td>$60,700.00</td>
<td>-2.34%</td>
<td>5.65%</td>
</tr>
<tr>
<td>I</td>
<td>8</td>
<td>8</td>
<td>0.013</td>
<td>2.25</td>
<td>1.00</td>
<td></td>
<td>$2,742,500.00</td>
<td>$89,600.00</td>
<td>3.27%</td>
<td>0.18%</td>
</tr>
<tr>
<td>J</td>
<td>8</td>
<td>8</td>
<td>0.013</td>
<td>0.80</td>
<td>1.20</td>
<td></td>
<td>$2,660,600.00</td>
<td>$7,700.00</td>
<td>0.29%</td>
<td>3.16%</td>
</tr>
<tr>
<td>K</td>
<td>8</td>
<td>8</td>
<td>0.013</td>
<td>2.00</td>
<td>1.00</td>
<td></td>
<td>$2,701,000.00</td>
<td>$48,100.00</td>
<td>1.78%</td>
<td>1.69%</td>
</tr>
<tr>
<td>L</td>
<td>8</td>
<td>8</td>
<td>0.013</td>
<td>2.00</td>
<td>2.00</td>
<td></td>
<td>$2,636,500.00</td>
<td>$16,400.00</td>
<td>-0.62%</td>
<td>4.04%</td>
</tr>
<tr>
<td>M</td>
<td>8</td>
<td>8</td>
<td>0.013</td>
<td>2.00</td>
<td>1.00</td>
<td>DR=1</td>
<td>$2,514,500.00</td>
<td>$138,300.00</td>
<td>-5.50%</td>
<td>8.48%</td>
</tr>
<tr>
<td>N</td>
<td>8</td>
<td>8</td>
<td>0.013</td>
<td>N/A</td>
<td>1.00</td>
<td>TF</td>
<td>$2,311,900.00</td>
<td>$340,900.00</td>
<td>-14.75%</td>
<td>15.85%</td>
</tr>
</tbody>
</table>

5.2 VARIATION OF PARAMETERS

A separate analysis of each of the varied constraints was completed so that the cost sensitivity of each constraint may be examined. Some constraints for the Panguitch system were shown to have a much greater impact on construction costs per incremental change than others. Some of this variety in the impacts of various constraints was due to the hydraulic principle involved, such as the great effect on minimum slope that varying Manning's 'n' value can have, and some was the nature of the Panguitch system itself, such as the small impact of varying the peaking factor because much of the system was easily conveyed by 8 inch minimum diameter pipe.
Variation of Minimum Pipe Diameter

Variation of this constraint yielded a greater overall reduction of construction cost than any other constraint save the use of the tractive force model. The allowance of 6 inch diameter pipe provided a possible reduction in construction cost of 5.02% over the base MODS design. There are many collectors throughout the system that have a design flow that could be conveyed by 6 inch pipe but have 8 inch pipe specified in order to meet state code for minimum pipe diameter. It is apparent that there is much to be saved by allowing the installation of 6 inch pipe in new sewer systems. In the case of Panguitch as much as $126,700.00 may have been saved from the final construction cost.

Variation of Minimum Depth of Pipe

Minimum depth of pipe is a constraint that is many times set deep in a community to assure that the basements in that community may be sewered. The citizens in Panguitch were asked if they wished to sewer their basements and they responded to the affirmative. During the construction of the Panguitch sewer system may citizens complained of the additional cost of connection to the system borne by the property owner due to the excessive depths of the sewer collectors within the right-of-way. It became apparent that there is more cost involved in the depth of a sewer than just installation of deeper main lines. The base minimum depth for sewer pipe in the community of Panguitch for the SEI design and the base MODS design was 8 feet. Various runs of the MODS program verified changes in construction costs with different minimum depths. Depths of 6, 7 and 9 feet were run in addition to the base run of 8 feet. The results of these various runs can be compared in Figure 5.2.1 below. In the range of values shown the variation of cost per
foot of minimum depth is almost linear resulting in an approximate overall change in cost of 2.0\% per foot of minimum depth.

**Figure 5.2.1 Minimum Depth vs. Cost**

![Minimum Depth vs. Cost](image)

**Manning's 'n' Variation**

The SEI design and the MODS base design use an 'n' value of 0.013. Variations in Manning's 'n' value from 0.011 to 0.014 were run on the MODS system to compare the changes in construction cost with the changes in the 'n' value. As discussed in Section 2.2 of this report an 'n' value of 0.013 is quite conservative and an actual savings may be made by the adjustment of this constraint with minimal change in the functionality of the system. The results of these various runs of the MODS system are shown in figure 5.2.2
below. The adjustment of the Manning's 'n' value to 0.011, a realistic value, can save as much as 2.82%, or $79,500.00, over the MODS base design for the Panguitch system.

**Figure 5.2.2 Manning's 'n' vs Cost**

![Manning's 'n' vs. Cost graph]

**Variation of Minimum Velocity**

Minimum velocity is a constraint intended to assure that solids do not settle out of the wastewater during the normal functioning of the system. As explained in Section 2.3 of this report the base velocity for the SEI and MODS run of 2-fps is a conservative catch all with little foundation in fundamental hydraulic principles. The state code currently mandates a minimum velocity of 2-fps. There is some room for argument for a lower minimum velocity for sewer collection system design, but the adaptation of the tractive force model would provide a far greater solution. MODS runs were performed for
minimum velocities of 1.5, 1.75 and 2.25 feet per second as well as the base value of 2.0-fps. Figure 5.2.3 demonstrates the relationship between cost and minimum design velocity from the various MODS runs for this system.

**Figure 5.2.3 Minimum Velocity vs. Cost**

![Graph showing minimum velocity vs. cost](image)

**Variation of Flow Multiplier**

The variation of a flow multiplier in the Panguitch system had a relatively small result on the construction costs for the system. This is primarily due to the minimum pipe diameter set at 8 inches. In most portions of the system 6 inch pipe is adequate but 8 inch pipe is specified to meet state code for minimum pipe diameter. The result is that flow can be increased or decreased within a reasonable range and the 8 inch pipe is still chosen for the design. Flow multipliers of 0.80, 1.20 and 2.0 were run on the MODS system and
compared to the base MODS run where the flow multiplier is the default 1.0. The results of these runs are shown in Figure 5.2.4 below.

Figure 5.2.4  Flow Multiplier vs. Cost

Using Downstream Diameters Less Than Upstream Diameters

Although in modern sewers the use of a downstream pipeline with a smaller diameter than an upstream pipeline will not cause excessive maintenance problems, in the Panguitch system design little relative cost savings is gained by allowing smaller downstream diameters compared to the adjustment of other design constraints. In the Panguitch system, allowing smaller downstream pipe diameters offered a possible savings of only 0.62% over the base MODS design. The Panguitch system does not have
many steep drops that would allow a smaller diameter pipe to have the same capacity as a larger upstream pipe. In a system with different topography the lifting of this constraint could provide a greater construction cost savings.

**Use of the Tractive Force Model**

Use of the tractive force model yielded the greatest construction cost savings compared to the adjustment of other design constraints examined in this report. As discussed in Section 2.3, use of this model to assure that solids do not settle in sewer pipes during normal operation is better founded in fundamental hydraulic principles than the minimum velocity method. The results of the MODS tractive force run demonstrate a possible savings of 5.50%, or $151,100.00, over the base MODS design of the Panguitch system. The tractive force model seems to present the option most fundamentally based on hydraulic principles and most cost-effective of those variations of design constraints examined within this report. With regards to project economics and hydraulically based design the tractive force model appears to provide the best alternative in sewer collection design to assure proper solids transport.

**Use of the Tractive Force Model and 6 inch Pipe**

Run P on the MODS system combined the benefits of using 6 inch minimum diameter pipe with the tractive force model of solids transport. The resulting cost benefit was a 14.75% savings over the base MODS design. This savings equates to $372,300.00 possible construction cost savings on the project. Debt service on this savings for a 20-year loan at 4% for a system with 594 equivalent residential units (ERUs) equates to a
savings of $3.84 per residential customer per month. At this level of construction cost savings and therefore savings to the end user, the modification of these two design constraints, would have been a great advantage to the citizens of Panguitch while the end result on the collection system would be minimal. It should be noted however that both of these design constraints are currently mandated by state code and the adjustment of either constraint would require a variance from the State of Utah. Currently the State of Utah Department of Environmental Quality does not encourage modifications to these design constraints.\textsuperscript{6}
SECTION SIX
CONCLUSIONS

6.1 EFFECTIVENESS OF COST OPTIMIZATION

When cost optimization takes a preeminent place among design objectives a significant portion of construction dollars may be saved. The application of the MODS program alone demonstrated a possible savings of up to 3.44% of construction costs over the original design. The application of further savings measures including the relaxation of the design constraint specifying 8 inch minimum pipe diameter and the application of the tractive force model of solids transport could further reduce construction costs up to an additional 14.75% over the already optimized MODS base design. These figures show cost optimization to be a successful mechanism for reducing design costs while not significantly reducing the effectiveness of the design.

6.2 EFFECTIVENESS OF MODS PROGRAM FOR OPTIMIZATION

The return in construction cost savings is great compared with the time investment necessary to run the MODS system. MODS has proven to be a useful tool for cost optimization of the Panguitch wastewater collection system. The base MODS run showed a significant savings of up to 3.44% over the original design when the same design constraints were applied. MODS further aided the cost optimization effort for the Panguitch system by providing a mechanism wherein 'what if' questions regarding design constraints could be easily and quantitatively answered with regard to final construction costs. These 'what if' scenarios provided insight to the workings of the Panguitch collection system as cost sensitivity analyses for various design constraints were performed using the MODS program and the cost effectiveness of the tractive force
model of solids transport became apparent. MODS not only aided the cost optimization process by finding an optimum design but by identifying those design constraints that could be adjusted to define a design procedure that better optimizes cost but does not significantly reduce performance of the system.

6.3 BEST DESIGN PRACTICES

Best design practices for design of wastewater collection systems aim to serve the needs of the client in the most cost-effective manner possible. Cost-effectiveness of design cannot replace system functionality; therefore, areas of cost reduction must be chosen carefully. The MODS system provides the designer with a tool that can aid in the cost optimization of a wastewater collection design. MODS enables the engineer to use best design practices to identify areas that can provide the greatest cost reduction without significantly hindering system performance. MODS also provides a mechanism that will allow the design engineer to reach an optimized design for a particular set of design constraints further reducing final construction cost. MODS is an effective tool for assuring that best design processes are employed to serve a particular client in the design of a sewer collection system.


