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Fostering Critical Thinking Through A Service-Learning, Combined Sewer Analysis Project In An Undergraduate Course in Hydrologic Engineering

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Abstract

The ability to exercise engineering judgment and think critically when put into unfamiliar situations is important to graduating engineering students as they begin their careers. However, many engineering courses focus on teaching students the background information and fundamental principles for a topic, without adequately engaging students in activities that cultivate and reinforce critical thinking or easily relate to real-world engineering projects. The result is often that students may 'know' things about a topic, but are far less able to 'do' engineering work in that topic. Upon entering the workforce, students will find that the overarching problem is dealing with uncertainty: information needed to solve the problem at hand is not neatly summarized in a question statement, and related textbook examples may not explicitly suggest the needed analytical procedure. How can instructors provide students the experience of 'doing' engineering work, and developing critical thinking at the university level that emulates the environment of real-world engineering practice? The application of service-learning projects, which use the EFFECTs-based technique of an underlying driving question, may contribute to the development of both practice-based experience and critical thinking.

In order to prepare undergraduate engineering students for the ill-defined, unfamiliar types of problems they will face after graduating, service-learning projects can be utilized to foster students' critical thinking through providing (a) a real-world context in which to solve engineering problems, (b) realistic data sources (including information that may be ambiguous, irrelevant, or incorrect), and (c) the industry-standard analytical and design software tools with which to integrate realistic information in solving the real-world problem. This paper presents the benefits of service-learning projects for emulating real-world engineering practice and it provides a profile of a service-learning project that combined elements of real-world engineering project and software tool utilization in order to perform a service learning project in the areas of hydraulic engineering and hydrology.

Why Service-Learning Projects?

Shapiro[1] presents three approaches to developing knowledge and skills; *lecture and readings* for "acquiring knowledge and becoming informed about techniques", *exercises and problem sets* as "the initial tools for exploring the applications and limitation of techniques and the *case method* for the development of philosophies, methodologies, and skills. These approaches do not necessarily provide real-world, critical thinking environments for students. Lectures, reading, and assigning homework problems from a textbook are an adequate approach to reinforce student familiarity with certain equations and relationships, but these homework problems do not adequately relate to the real-world projects that the students will encounter in their careers. Even a detailed explanation of how the assignment relates to real-world projects will not truly connect for the students.

The case-based or problem-based method[2] begins to present real-world experiences to the students, but the specific conditions of the case are given to the students and the case typically addresses one issue for clarity of learning. Students cannot conduct a site visit to obtain visual cues or verify data. Students analyze and discuss the problem, then ask questions which are provided predetermined answers to lead the students to the solution that was arrived upon in the real-world design. The solution is known by the instructor from the beginning. Additionally, the students also know in the back of their minds that the instructor knows where the case/problem is leading, therefore removing the real-world feel from the case method, and robbing students of an opportunity to feel additionally invested in their work since it may yield an actual benefit to the intended client or recipient.

Recent papers have presented and discussed the benefits and lessons learned with project-based and service-learning project activities for providing a real-world experience for students[3,4,5]. Service-learning projects provide the additional elements of realism and student engagement that take case-based learning to the next level of pedagogical efficacy. By following a format similar to the project presented in this paper, service-learning projects can be utilized to foster students' critical thinking through providing a real-world context in which to solve engineering problems. The real-world context is generated by:

1. Providing a driving question that has many unknown issues (for the student, instructor and project owner) and does not have a predetermined solution. *This prevents the instructor or project owner from steering the project to specific issues on the project.*
2. Providing an opportunity for site visits. *This provides the ability to see the project first hand which makes the project real for the students. They also have the opportunity for visual understanding and verifying the provided data.*
3. Providing data that may be ambiguous, irrelevant, or incorrect. *This promotes critical thinking to determine which data should be utilized in the analysis or design. Students may also be required to develop or assume data for the project, which is done daily in engineering practice.*

4. Requiring the use of industry standards. *Industry standards and codes (local, state, national) are utilized on a daily basis on engineering projects. Determining the required design standards or codes is a fundamental step on real-world engineering projects.*
5. Utilizing common industry design software. *Engineering software is utilized more every day in industry. Students must utilize software from their undergraduate studies or learn new software that is required to complete the project.*
6. Assuring the students that neither the instructor nor project owner knows the answer to the driving question. *This gives ownership of the project to the students and challenges them to provide a response to the driving questions. They direct their questions to solving the problem and not figuring out a predetermined answer.*

The combined sewer analysis project presented in the paper provides many of these contexts providing an excellent opportunity to experience real-world engineering.

Combined sewers are generally:

1. <u>Ubiquitous</u>, being found throughout many communities in the United States, particularly in the eastern half of the country and in the Pacific Northwest. The abundance of combined sewers includes many older, well-established cities in which universities are often located. Combined sewers (that are old, deteriorating, and in need of attention) are not difficult to find.

2. <u>Nearby</u>. Having a project in close proximity to the university itself enables students to visit the project site to perform field-checks of GIS data, conduct characterization of surface conditions (e.g., land use types, cover conditions, etc.), and promotes a sense of "buy-in" among students, who are able to directly observe the community they are working to serve through their project. Students' interest and engagement are amplified if they know the project is 'real.'

3. <u>Aging and in need of improvement</u>, making them excellent subjects with which to illustrate principles of analysis and targeted optimization. Furthermore, since these aging systems will ultimately require engineering services (either to retrofit and upgrade them, or repair them after failure), obtaining engineering experience with such a subject may give students experience that is someday useful in their subsequent employment.

4. <u>Underfunded</u>, which increases the probability that the organizations responsible for combined sewers will welcome project cooperation with undergraduate students. This is particularly true for utilities under EPA mandate to improve service, and where there is a perception that "waste" water could instead be redirected towards beneficial uses.

5. Easily modeled using industry-standard hydrologic / hydraulic analytical and design software. There is an inherent modularity to sewer networks, such that instructors can adjust the scale and complexity of a project by simply varying how large of a 'sewer-shed' to include in the project boundaries.

A Service-Learning Project in Hydrologic Engineering

Hydrology and applied hydraulics courses are often taken by undergraduate civil engineering students during their senior year, after having already taken one or more courses in fluid mechanics and/or hydraulic engineering. As such, these students often have already obtained the fundamental foundation upon which analytical and design projects can be based. With the ever-increasing emphasis on computer-aided analysis and design, academic programs have reason to identify opportunities to teach students ways to integrate basic engineering knowledge and principles into software applications. While the core knowledge concepts of hydrology (e.g., precipitation, infiltration, runoff, hydrographs, etc.) cannot be replaced with software instruction, once these principles have been introduced, learning can be supported by showing students the basics of how to use hydrologic and/or hydraulic software, and then allowing them to independently utilize these tools to solve a problem in the same way that they will be asked to upon graduating from the university and beginning their engineering careers.

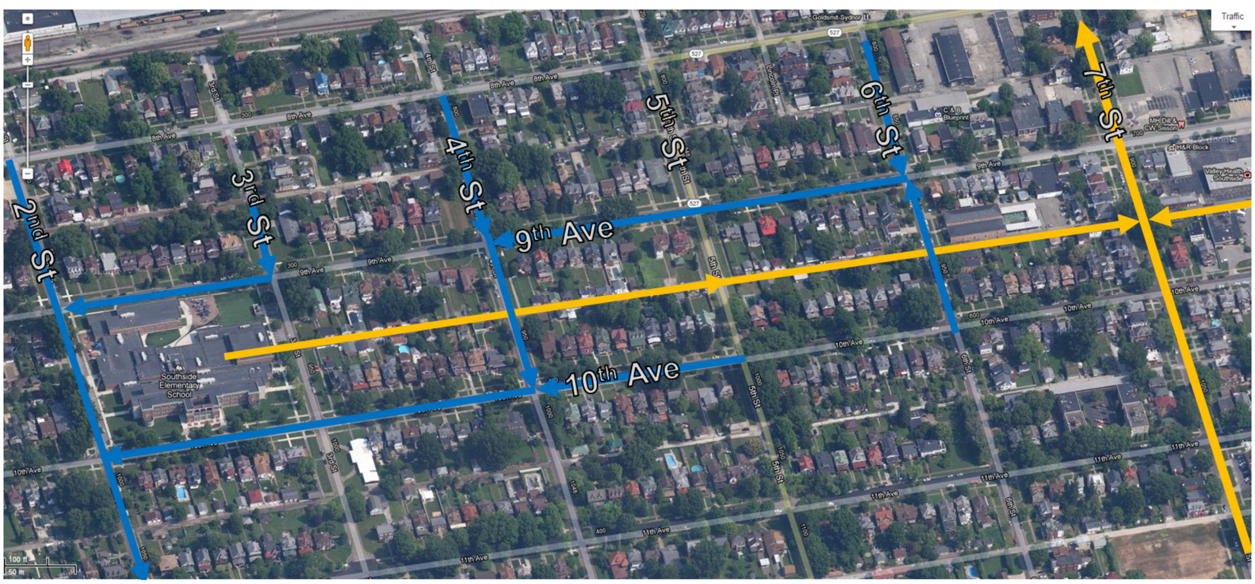

Figure 1 – Illustration of project area: a 4x1 block area in Huntington, WV.

Senior-level undergraduate students enrolled in a first course in hydrology were introduced to the following real-world scenario by a speaker from the local sanitary board: during wet-weather events, the combined sewer in a certain neighborhood occasionally experiences incidents where the combined stormwater runoff and sewage flow rates exceed pipe capacity (see Figure 1). When this occurs, wastewater enters residents' basements, causing inconvenience and damage.

The local sewer utility would like to evaluate whether residential disconnection of roof drains (i.e., the rain gutters on peoples' homes) will lead to a significant reduction in the frequency and severity of these basement backups. The sewer utility's actual mapping resources for the project area are provided to students, showing the pipe network details that are known. Students are also directed by the instructor to additional sources of information, such as plat maps from the county GIS office, publicly-available aerial photography, and field visits to the project area, which is approximately two miles from campus.

Students are asked to first develop a schematic understanding of how stormwater flows over and through the project area. This includes a site assessment of how many residents currently have connected roof drains, student-estimated rational runoff coefficients for lots, the flow capacity of the existing drainage network, and time of concentration relationships.

After gathering information and documenting a conceptual hydrologic scheme for the area, this information is translated into a computerized model of the project area and its hydrology using an industry standard software tool (i.e., Bentley StormCAD). Through repeated analysis of various roof-drain disconnection percentages (e.g., 20% of existing homes are disconnected, 40%, 60%, etc.), students characterize the reduction in stormwater flows that can be expected for the project area. In this way, students can then address the driving question of how effective roof-drain disconnection might be at reducing problematic sewer backups. Through experiencing a real-world engineering analysis project, students are able to provide a valuable service to the local sewer utility, and become more proficient at critical thinking and problem solving in a realistic environment, with realistic tools and resources.

Project Integration into Course

In Marshall University's "Hydrologic Engineering" course (enrollment = 12), students learned of the course project on the first day of the course, when the basic principles of combined sewers, wet-weather flows, and rainfall-runoff relationships were also introduced in an introductory and qualitative way. The problem of combined sewer backups was used as a conceptual outline for the course, highlighting different aspects of what contributes to the problem and how each can be quantified or understood. In a single 50-minute lecture, students were exposed to ideas such as temporal distribution of precipitation, time of concentration, degree of imperviousness of land cover, variation in infiltration capacity of soil, and visualization of runoff flows with hydrographs. Upcoming units within the course were tied to a real-world, local illustration that students could subsequently think back to during more in-depth lectures. "Context" is especially valuable when teaching the abstract concepts found within the topic of hydrology.

Through both ordinary class lectures and their efforts on the project, students repeatedly confronted the driving question: *what would be the effect of disconnecting residential roof-drains* *on a combined sewer line prone to overcapacity failures that cause basement backups.* The use of driving questions to foster critical thinking and create an environment where students can develop engineering judgment has been advocated in an educational methodology known as 'EFFECTS' (Environments to Foster Effective Critical Thinking). The EFFECTS methodology[6,7,8] is a modular approach to supporting critical thinking, and can be utilized in engineering courses at every level. In senior-level courses where design can be incorporated into the curriculum, EFFECTS is a particularly useful technique for sequencing active learning exercises with core knowledge principles that are needed to explore the ultimate driving question.

Project Area Background

For many years, residents along a one-by-four city block stretch of combined sewer have suffered from flooding caused by excessive flows in a 24-inch combined sewer. The combined sewer in question receives street-level stormwater flows from roadside catch basins at only a single point, and the majority of stormwater is from residential downspout connections. Homes in the area predate regulatory prohibitions against roof drain connections by several decades, and thus more than 90% of roofs drain to the combined sewer. Disconnection of roof drains from the combined sewer, and subsequent surface routing of flows to a nearby storm sewer via roadside gutters (see Figure 2), may reduce the frequency of problematic combined sewer backups.

Figure 2 – Illustration of driving analytical question: *what will be the effect of various percentages of roof-drain disconnection upon the over loading of combined sewers during wet weather events?*

For purposes of modeling, students used the sanitary board's LTCP-specified wastewater flow rate of 140 gallons per resident per day, scaling flows upward to simulate peak hour conditions coinciding with the wet-weather event. Precipitation intensity, duration, frequency data was obtained using the NOAA Atlas 14 based Precipitation Frequency Data Server (PFDS). Students estimated times of concentration by field visits to the project area during actual wet-weather events, and observing gutter flow velocities, estimating lateral pipe velocities, and measuring flow distances.

Project Sequence

Rather than immediately utilizing the supplied hydrologic and hydraulic software package (i.e., Bentley Systems' StormCAD) to build a model of the project area, students were required to first gather data about the project site, summarize that data, and create on paper a schematic representation of how water moves within the neighborhood under analysis.

The primary phases of the student project included:

1. Kickoff meeting with combined sewer operator. Towards the beginning of the semester, a representative from the sewer utility attended class and presented information about the problem in the project area, their experiences and challenges with respect to the combined sewer, and the regulations and other motivating factors for attempting to mitigate the problem.

   Hearing from outside speakers helps to create an atmosphere of "reality" in students' minds with respect to the project, and also is a good chance for students to learn more about the challenges faced in the 'real world' of engineering practice. The question that students sometimes ask, "is this really important?" is readily banished when an outside authority explains that sewage flowing into residential basements is the side-effect of undersized, failing combined sewers.

2. Review of available data. The sponsoring agency may have paper maps, GIS data, past studies, master plans, and/or reports for the subject area, and other information that can be useful to students. In the project summarized herein, the course instructor obtained the available data from the wastewater utility and reviewed it to become familiar with its coverage, relative precision, what gaps and errors may exist, and what else students would need to learn through field visits before beginning their project.

   Non-perfect data is an inevitable reality in the real world of engineering practice, and students were not shielded from that reality in this project. The uncertainties and contradictions that arise when using multiple data sources that were assembled by different people at different times can sometimes be a shock for recent graduates who are accustomed to having all of the 'givens' in a particular problem served up to them in a single succinct paragraph. Thus, easing engineering students into an understanding of such issues before graduating can lessen the shock of uncertainty once they begin working.

Although much of the information that students would need for their project was indeed available (e.g., pipe locations, material types, and diameters; pipe and manhole invert elevations; catch basin locations; etc.), there were several discrepancies in terms of which way water should flow in a few of the pipes, whether a certain catch basin was connected to the combined sewer network or a nearby storm sewer, and missing invert elevations at some of the junctions. These discrepancies were ideal opportunities for students to practice engineering judgment through making reasonable assumptions, for example to realize that they could make up for missing invert elevations by continuing pipe slope patterns. Likewise, a review of data gaps and discrepancies showed students the value of going into the field to gather information and eliminate uncertainties.

3. Field visit to characterize surface conditions. Students were broken into several groups of 3-4, and were assigned to gather data in the field. Following an in-class discussion in which students were led to identify what field data would need to be collected, the students gathered information related to: whether a home's roof-drains went underground and potentially were connected to the combined sewer or drained into the yard area; the relative fraction of a lot's impervious surfaces vs. green (pervious) surfaces; an estimation of what direction surface water flows (i.e., towards which catch basin).

   Students accessed and printed out plat maps from the county GIS website in order to have a common scheme for referring to each lot within the project area. Having these maps available also aided in keeping track of lot areas, shapes, and in constructing house-by-house representations of rooftop areas, and in later calculating time of concentration.

4. Summarizing obtained parameters. Student groups covered individual areas within the project site, and thus it was required for them to summarize and report the relevant parameters so that this data could be shared and accessed among each group.

5. Development of a conceptual model. Using paper maps and aerial photographs, students were required to create a conceptual model of the project area before building their models using the computer. The purpose of this requirement was to ensure that all of the needed data was, in fact, available to students so that they would not make ill-considered assumptions at the model stage, and so ensure that 'how things work' was understood in

student minds before translating that understanding into symbolic catchments, conduits, junctions, inlets, and outlets.

6. Building a network model using software. For sake of simplicity and standardization, a scaled aerial photograph was provided to student groups which could be imported into StormCAD and on top of which could be drawn the network model. In this way students were able to utilize scaled conduit lengths, and ensure that pipe locations corresponded with their actual location in the field. Students utilized the utility-supplied data and their field measurements, which had all been translated into a summarization of known parameters, to enter in other model characteristics such as pipe material type, pipe diameter, invert elevations, and catchment areas.

   Since the network being modeled is a combined sewer, which will contain storm runoff and residential wastewater flows, a fixed base flow was utilized to represent the quantity of wastewater that would be present in the network during critical events.

7. Analysis and redesign. Utilizing intensity-duration-frequency data that is available on NOAA's "Precipitation Data Frequency Server", students entered precipitation intensities corresponding to 2-, 5-, 10-, 25-, and 50-year storms. The underlying analytical methodology was to investigate which pipes in the network failed the soonest; in other words, when storms of increasing intensity were modeled, students worked to identify the network elements that had the least capacity relative to the predicted flows that would be present, based on the upstream catchment areas and sewage-contributing residential population.

   Since a primary motivation for the project was to understand how roof drain disconnection would affect the frequency of pipe network failure (and thus the frequency and severity of basement backups), students incrementally adjusted the runoff coefficient and/or catchment area that contributed to the combined sewer. Disconnected roof drains would result in rainwater flowing over residents' lawns, resulting in a favorable decrease in runoff volume due to infiltration. Due to a nearby stormwater network, some of the additional surface flows that would come from roof-drain disconnection would avoid entry into the combined network altogether.

   Once a characterization of failure vs. return period storm had been made, students then worked to identify the low-hanging fruit, such as particular pipe segments that could be resized to enhance overall network performance, or certain catch basins that could be redirected from the combined sewer to a storm sewer approximately one block away.

8. Reporting. Students prepared written reports summarizing their findings, including annotated, printed maps of network performance in different return period storms. These reports were provided to the instructor so that suggestions could be provided prior to oral presentation of results to the sponsoring sewer utility.

Each three-person student group was assigned a different portion of the overall project area to gather field data for. Groups were instructed to avoid other teams in determining an analytical matrix in order to promote the independence of each group's solution. Each of the five groups did utilize different assumptions and methods in terms of aggregating individual residential lots into larger catchment areas, how many sub-pipes to break network mains into for purposes of analysis, and how to translate roof-drain disconnection into their numerical model.

A sample of student work is presented in Figure 3, depicting the drainage network that was modeled, and flow rates (and percent of capacity) in each pipe.

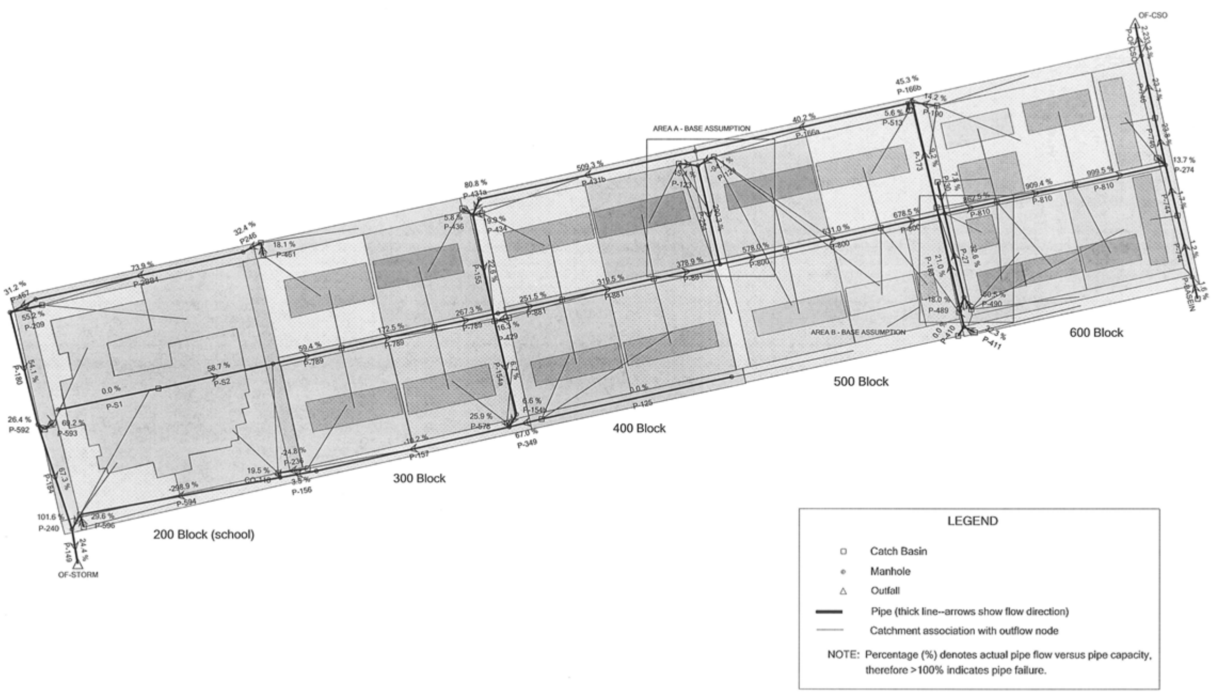

Figure 3 – Student-generated analysis of project area under current conditions, 10-yr storm.

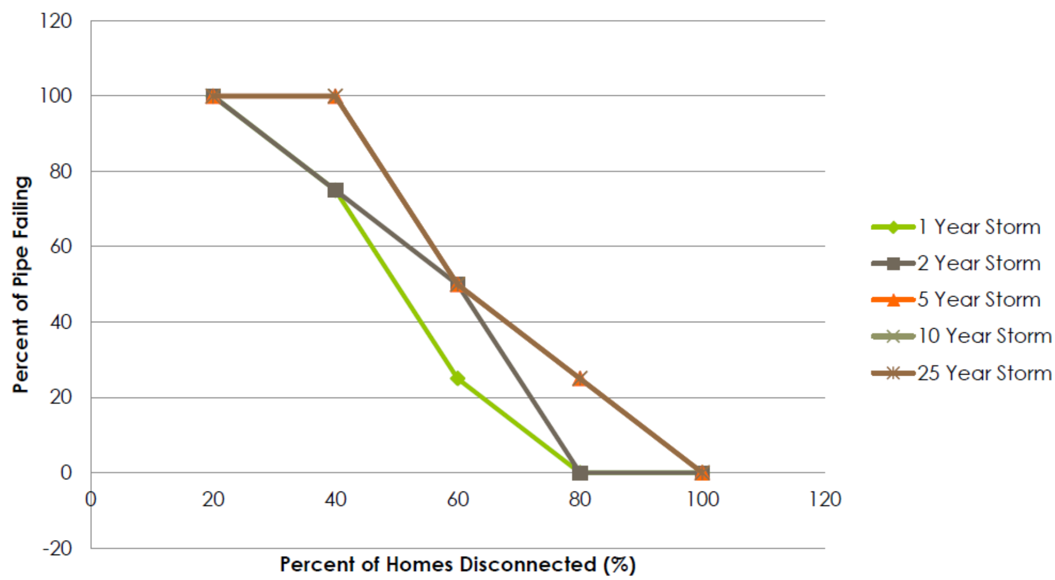

Figure 4 – Student-generated analytical results showing relationship between roof-drain disconnection and pipe network failure.

The five student groups developed similar conclusions in terms of what size storms would cause failure in the existing drainage network (see Figure 4). Likewise, the different student groups predicted similar expected flow rates when achieving various roof-drain disconnection rates (e.g., 20% disconnection, 40%, 60%, etc.) among residents in the project area (see Figure 5).

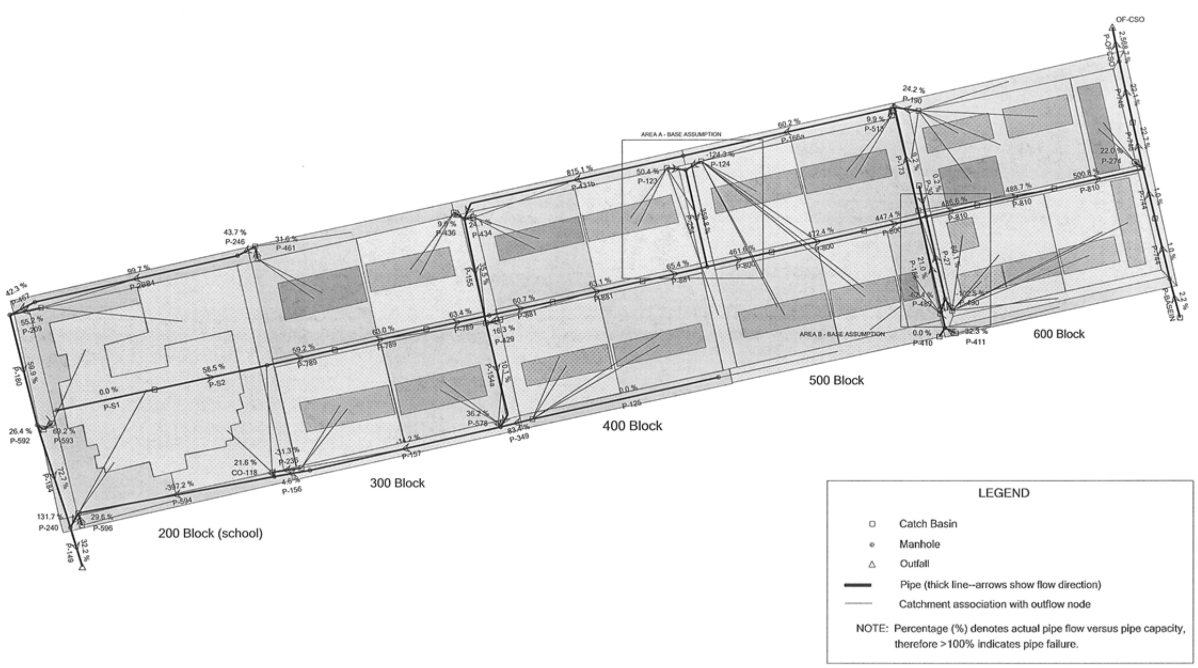

Figure 5 – Student-generated analysis of project area under 100% disconnection of residential roof-drains, 10-yr storm.

Benefits to the Utility

The outcome of student analyses was to answer the utility's original question of how much roof drain disconnection would be required to avoid further network failures in the project area: approximately 80%. Additionally, students identified a street-level catch basin that is connected to the combined sewer and contributes substantial storm flows. This catch basin may be a candidate for disconnection to the combined sewer, being instead tied in to an adjacent storm-only collection network.

In a regulatory environment where utilities are anxious to address the need to reduce Combined Sewer Overflows (CSOs) as mandated by their Long Term Control Plans (LTCPs), there is a pressing need to understand drainage network performance so that improvements can be identified and implemented. Likewise, stormwater pollution permits require a 'public outreach and education' element in their MS4-mandated stormwater management plans, so engineering student involvement in combined sewer analysis projects is a win-win situation. Utilities win because they are able to show the EPA that they are engaged in cooperation with local educational institutions, and they also win because students can conduct evaluations that a utility may not otherwise be able to afford, are sometimes able to uncover relationships and make suggestions that have been previously overlooked, and have the potential to make meaningful improvements. Students win because they are able to apply principles of hydrology to a real-world project (which enhances both learning and retention of concepts), they are able to learn a new software package (which gives them useful experience and promotes confidence in their own abilities), and they become acquainted with some of the challenges of engineering work they will be engaged in upon graduation.

Conclusion

The students who participated in the project described in this paper had an overwhelmingly favorable response, and in an online survey that was administered at the end of the project, students unanimously agreed that the project had been "very effective" as a way of helping them to learn hydrology. Students also universally agreed that the project had been a significant amount of work; some comments that were received indicated a wish that they had organized their data-gathering or network-building methods differently in retrospect (e.g., planned a preliminary analytical matrix before gathering field data).

It is difficult to individually assess students on work completed in group activities such as described in this paper. From the group reports and presentations that are typically given at the conclusion of these types of activities, it is not clear which students did what work, and whether some students may have bypassed the intended learning opportunities. However, the skills developed by students while completing such a project could be evaluated through the same mechanisms that would be used if the skills were taught in a different way (e.g., if software proficiency had been developed through tutorial assignments rather than by analyzing a combined sewer network), namely quizzes, examinations, and one-on-one demonstrations of proficiency from the student to the instructor.

By introducing students to the tools, challenges, and satisfaction for a job well-done that they will experience as engineering professionals, combined sewer analysis is an easy to implement course project that can be adopted and adapted at locations across the country. In the hydrologic engineering course identified in this paper, analysis and redesign of a combined sewer system has been a class project for two consecutive years, and additional related projects are anticipated in future semesters.

Acknowledgement

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