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# The Engineering of Green Infrastructure and Stormwater Management Practices

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## Introduction

The state of Delaware is the lowest lying state in nation and much of my school district is mere feet above sea level.[1] A state as low lying as Delaware is vulnerable to frequent flooding during coastal storm events, extreme tides, and during heavy rainfall events. Much of coastal Delaware is also extremely at risk for flooding related to sea level rise. Additionally, the high percentage of developed land in the state (especially in New Castle County) contributes to a high degree of impervious surfaces which exacerbates issues of flooding. There is also a strong link between a warming climate and more frequent/intense flooding due to an increase in the intensity of rainfall events.[2] What makes this untenable situation even worse is that flood plain boundaries and flood maps have not been adjusted to reflect this new reality.[3] In order to mitigate the risk of flooding in low lying areas and to deal with stormwater runoff, the state has implemented several stormwater management practices.

I would like to focus on two specific areas in New Castle County: the area just south of the town of New Castle, and the neighborhood of Southbridge in Wilmington. These are two areas chronically plagued by flooding, and they also represent different parts of my school district. My students live and work in these communities. They have a direct connection to a significant environmental problem that can be and is being addressed with engineering solutions. Of specific interest is Delaware State Route 9. Just south of New Castle, Route 9 is aptly named River Road, as it follows the Delaware River and quite literally can become a river after significant rainfall or at extreme high tides. North of New Castle, Route 9 leads to the neighborhood of Southbridge, one of the lowest lying areas in the city of Wilmington. This neighborhood is surrounded on three sides by the Christina River and was built on filled in marshland. Just like River Road to the south, this area floods during periods of significant rainfall and during extreme tides. In this unit I teach students about the science and engineering practices involved with designing and implementing effective storm water management systems.

## Rationale

William Penn High School is a public high school in the Colonial School District in New Castle County, DE. It is the only high school in the district and is the largest high school in the entire state, serving between 2,000 and 2,200 each year across grades 9-12. The district is considered suburban/urban fringe and serves a diverse population in terms of both race and income. Several years ago, William Penn began focusing on the growth of Career and Technical Education (CTE) programs that provide opportunities for students to experience a vocational-type education while still being provided with the traditional college preparatory education typical of public schools. Such a shift has allowed the school to retain students who may otherwise attend one of the four area Vo-Tech schools. Students entering William Penn chose a degree program to specialize in within one of three college academies: Business, Humanities, or STEM. Degree programs within the Business College Academy include Air Force JRTOC, Business Administration, Culinary Arts, Financial Services, and Accounting. Degree programs with the Humanities College Academy include Behavioral Sciences, Communications, Teacher Academy, Legal Studies, International Studies, and Visual and Performing Arts. The STEM College Academy offers degree programs in Agriculture, Allied Health, Computer Science, Construction, Engineering, Manufacturing, Mathematics, and Science. William Penn also offers 25 Advanced Placement courses, the largest number of any school in the state. This dual focus on college and career readiness has greatly improved the school culture and the school's image in the community, which has translated to the growth in the student population.

This growth in student population and interest in the sciences helped me justify the need for adding AP Environmental Science to the course catalog in the 2016/17 school year. Students enrolled in the Agriculture degree program can specialize in the Environmental Science pathway, which requires them to take two years of on-level environmental science before enrolling in APES as their capstone course. Since the course is officially part of a CTE program, students are expected to finish the course with some sort of job-applicable skill. To me, getting students to think critically about environmental problems and potential solution is my primary goal, but am always looking for ways to address those job skills as well. Learning how to study an environmental problem and propose and implement an engineering solution is certainly a job skill that would serve students well as they move into the workforce. Such skills include working with topographical maps and hydraulic runoff models to study how different surfaces and geographies impact runoff and flooding.

This seminar also provides me with the opportunity to address two major shortfalls of my course. The first issue is that my course has always lacked a deep and meaningful connection to the solutions to environmental problems. We talk ad nauseam about the myriad environmental problems we face, but spend little time discussing the solutions to those problems. To address this problem, College Board has made a concerted effort in their redesign of the course to include more solution-oriented content into the course. Last year I tried incorporating more anecdotal stories about environmental successes, like the Montreal Protocol and the impacts of the Clean Air and Clean Water acts. And while this was a good first step, I find the course still lacks meaningful content that incorporates the science and engineering of those solutions.

The second issue is that my course lacks true connection to the local environment. Many of the environmental issues we discuss in class, such as deforestation, increasingly frequent droughts and wildfires, contamination of drinking water sources, and even climate change to some degree lack an immediate and tangible connection to the community around us. But because urban flooding is so frequent in certain portions of our community, the issues related to stormwater management and land use are front and center. Focusing on this issue and developing a high quality curriculum unit that pulls back the curtain on how stormwater management techniques functions is a solid first step in addressing these shortfalls and improving my course for all students.

## Learning Objectives

I am currently exploring the topic of land use for a local seminar through the Delaware Teachers Institute. The environmental impacts of land use change vary in nature and degree and include increased stormwater runoff from more developed areas, enhanced urban heat island effects from replacing natural materials with concrete and asphalt, habitat loss for bird, reptile, and small mammal species, and increases in noise and light pollution from human activity.[4] Another aspect of land use change in Delaware is the increase in impervious surfaces as land is developed. Problems associated with impervious surfaces include urban flooding, increased storm water runoff (which increases nonpoint source pollution), higher peak flood events, and decreased infiltration.[5] That connection between land use and stormwater is the driving force for linking this unit with my local one.

This unit first focuses on land use and impervious surfaces and surveys the traditional gray infrastructure that most of the country employs in stormwater management. I then turn to an investigation of the green infrastructure techniques being deployed to more effectively manage stormwater in urban areas. Much emphasis is given to the science and engineering of constructed wetlands, swales and bioretention basins, green roofs, rain gardens, and permeable pavements. I discuss the flooding specific to the Southbridge neighborhood and the River Road area and present a simple stormwater runoff model for studying the impact of different management plans of runoff flow.

The central objective of the unit is based around students using their knowledge of stormwater management and basic engineering design principles to propose an effective plan for managing stormwater in Southbridge and along the Route 9 corridor south of New Castle. To that end, students learn the basics of stormwater and its connection to land use and impervious surfaces, how green infrastructure is improving stormwater management, use rudimentary hydraulic stormwater models to investigate how different geographic conditions and constraints impact effective stormwater management, and learn about how urban and suburban areas can plan to alleviate the problems of stormwater runoff. Students also complete a modified Free Response Question (FRQ) on the topic to demonstrate mastery of the unit.

## Content Objectives

### Land Use and Impervious Surfaces

Impervious surfaces are any materials that prevent the infiltration of water into the soil and groundwater. Examples include roads, rooftops, driveways, parking lots, and sidewalks.[6] The dominance of impervious surfaces in developed areas is a relatively recent development, emerging with the advent of interstate highway system and the suburban sprawl it enabled. Under pre-development conditions, natural surfaces are able to absorb and infiltrate rainfall. But when they are developed and replaced with impervious surfaces, the local water cycle is dramatically impacted,[7] as depicted in Figure 1. The major impacts include reducing shallow and deep infiltration, reducing evapotranspiration, and significantly increasing the amount of surface water runoff.

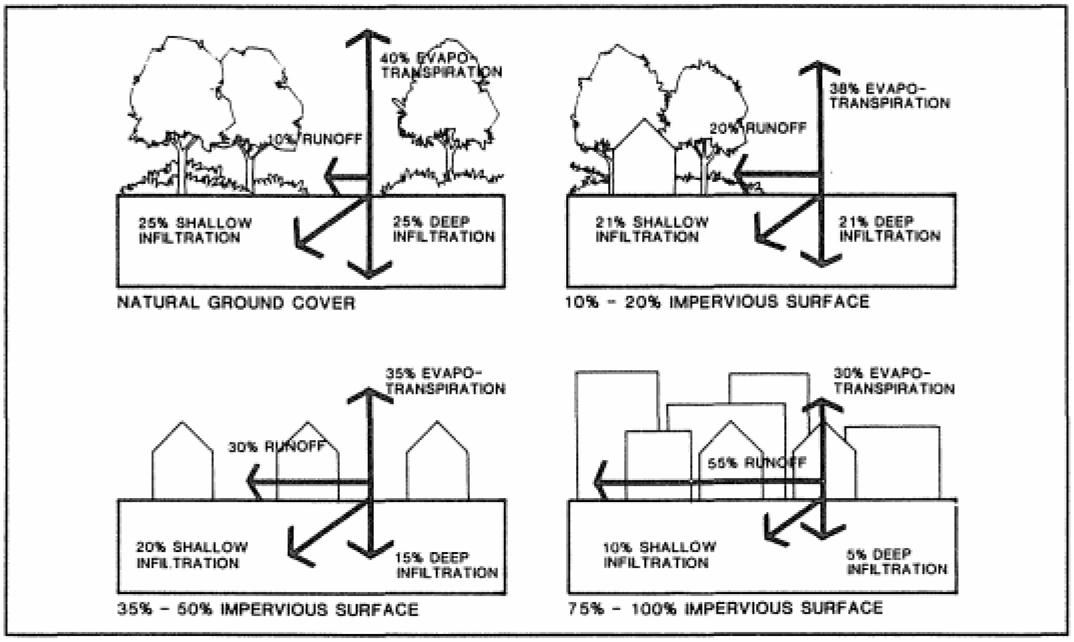



Figure 1: Water cycle changes associated with urbanization.[8]

Historically, northern Delaware was mostly forest,[9] with coastal wetlands bordering the Delaware River and its tributaries.[10] However, as demonstrated in Figure 2A, almost all of this part of the state has been developed to some degree. The urban core of the city of Wilmington is nearly all high intensity developed, and suburban sprawl can be seen as the high degree of medium intensity developed land surrounding the city. Some pockets of forest and cultivated land are still present, but mostly as islands amidst heavily developed land. The floodplain of the Christina River (pictured in light blue running diagonally in the center of the image) and coastline along the Delaware River are covered by woody or herbaceous wetlands, though their extent has been significantly reduced over the past century.[11]

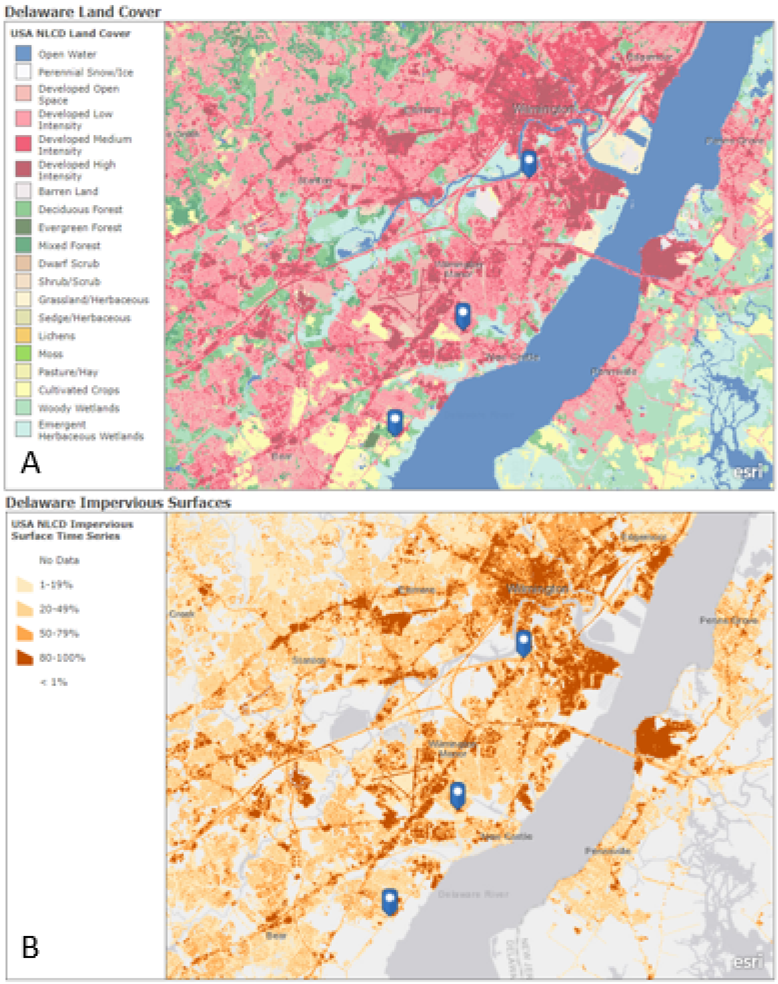



Figure 2: A: Land Cover in Northern Delaware Area.[12] Data provided by National Land Cover Database through Esri and ArcGIS. B: Impervious Surface Cover in the Greater New Castle, Delaware Area. Data provided by National Land Cover Database through Esri.[13] The northernmost blue marker denotes the neighborhood of Southbridge, the central marker denotes William Penn High School, and the southernmost marker denotes the Route 9 Corridor.

The relationship between land cover and impervious surfaces is driven home by comparing Figures 2A and 2B. The areas with the highest percentage of impervious surfaces are in the areas with the greatest amount of development. Major roadways can be seen as thin, interconnected strips of highly impervious surfaces, and major population centers or industrial areas are marked by spots of intense orange. Remaining areas of low impervious cover coincide partly with the "natural landscapes" bordering the Christina River and the coast of the Delaware River, as well as the limited forested and cultivated areas.

**Stormwater Runoff and Gray Infrastructure**

Stormwater is defined as the portion of precipitation that does not naturally percolate into the ground or evapotranspirate, but instead flows via overland flow, interflow, channels, or pipes, into a defined surface water channel or constructed infiltration facility.[14] In this unit, stormwater and stormwater runoff are used interchangeably. There are several traditional methods of managing stormwater runoff, commonly referred to as gray infrastructure.

Gray infrastructure is designed to move stormwater away from the built environment, and has traditionally been deployed to collect and convey stormwater from impervious surfaces such as parking lots, roadways, and rooftops into a piped system that then discharges into a local surface water body such as a stream, river, or lake.[15] Examples of gray infrastructure include curbs, gutters, grates, drains, subsurface piping, and collection systems. A combination of these specific pieces of infrastructure make up a storm sewer system, with the express purpose of rapidly clearing locations of stormwater.

***Environmental Impacts of Gray Infrastructure and Stormwater Runoff***

The rapid delivery of stormwater runoff to surface water bodies by gray infrastructure is problematic for several reasons. These problems include routine localized flooding, erosion of stream banks, alteration of stream/river hydrology, and transfer of surface pollutants into local surface water bodies.[16] Routine flooding, erosion of stream banks, and alteration of stream/river hydrology have to do directly with the purpose of gray infrastructure. Recall that such systems are designed to rapidly move water away from the built environment. In periods of heavy rain, this system can become quickly over loaded, resulting in a backup of storm drains, which leads to localized flooding, especially in low-lying areas. Channeling stormwater from impervious surfaces into pipes greatly increases the velocity at which water enters streams, increasing its erosive potential and thus altering the stream/river hydrology. In areas where the stormwater and sewer systems are combined and routed to a treatment facility before discharge, an increase in stormwater flow can lead to a combined sewer overflow, where the volume of water is too great for the treatment facility and must be released untreated.[17] This has significant environmental impacts, some of which are discussed below. In summary, the underground sewer systems so often employed to manage stormwater are problematic because they lead to the rapid release of polluted water into local surface waters,[18] excessive flows into local surface waters,[19] and backflow into streets and homes/businesses when the system is combined with sewage collection and overtaxed from a storm event.[20]

The transfer of surface pollutants into local surface water bodies is a substantial threat to stream, river, and pond/lake ecosystems: any pollutant on an impervious surface can potentially be washed away into a local creek or other water body during normal rain events. Such pollutants include oxygen depletors, pathogens, metals, nutrients, and still others that impact pH, turbidity, and total dissolved solids.[21] Oxygen depletors include ammonia and other constituents that increase the biochemical oxygen demand (BOD) of a water body, such as the organic compounds in sewage. Enteric pathogens can be released and re indicated by the presence of fecal coliform. Common metals in stormwater runoff include lead, mercury, and cadmium. Nitrogen and phosphorous are the primary nutrients carried by stormwater runoff and can cause eutrophication, a process that leads to oxygen and pH fluctuations and can lead to the release of toxins by blooming algae. Stormwater runoff can also directly impact the turbidity, and salinity or total dissolved solids in a surface water body.[22]

## Green Infrastructure

A changing stormwater management paradigm has begun to emerge in the last fifteen years as engineers and urban planners have turned to green infrastructure to help manage stormwater in developed areas.[23] This changing paradigm attempts to recognize the value of stormwater in urban areas instead of treating it as a problem to be discharged to adjacent water bodies, and has resulted in the development of such things as constructed urban wetlands, vegetated swales, and bioretention basins.[24] Other examples of green infrastructure include green roofs, rain gardens, and permeable pavements.[25]

In stark contrast to gray infrastructure, green infrastructure is designed to mimic nature and capture rainwater where it falls, with the chief goal of reducing, slowing, and filtering stormwater runoff into local waterways.[26] The most commonly deployed examples of green infrastructure are retention and detention facilities, which are used in conjunction with the gray infrastructure described above. Retention facilities are designed to hold stormwater and do not contain an outlet. Water leaves through evapotranspiration or through infiltration into the soil. Detention facilities are designed to temporarily hold water before it is released at a slow rate, with little infiltration into the surrounding soil.[27] These work well in suburban settings where impervious cover percentages are lower and less connected than in urban settings. In urban areas, where space is limited and retention/detention facilities are not feasible, the use of green roofs, vegetated swales, rain gardens, and impervious concrete have gained popularity.[28] Where geography permits, constructed wetlands have shown significant promise for retaining and treating stormwater runoff.[29] According to the USEPA, using such techniques has the effect of reducing localized flooding, improved community aesthetics, increased community socialization, increased property values and job opportunities, decreased economic and community burden associated with flooding, and diverse, location specific environmental, social, and economic benefits.[30]

***Constructed Wetlands***

Constructed wetlands (Figure 3A) are those that are created in areas that were not previously wetlands, typically to absorb and filter stormwater runoff before its discharge into a surface water body.[31] At their simplest, they are artificial, shallow, and extensively vegetated water bodies designed to absorb and treat stormwater. Ancillary benefits provided by constructed wetlands include improving community aesthetics, offering recreational activities such as birding, and ensuring the availability of water for re-use.[32]

A typical constructed wetland consists of three zones: an inlet zone, a macrophyte zone, and a high flow bypass channel. The inlet zone is the area of the wetland designed to take in flow, and typically by placing a sedimentation pond upstream of the desired wetland area. This zone acts as the first step in the treatment of any pollutants in incoming stormwater as coarse particles settle out. Water then moves into the macrophyte zone, a shallow area with extensive emergent vegetation. The specific type of vegetation in this zone is dictated by the water depth. In general, a constructed wetland contains four vegetation zones: shallow marsh vegetation, marsh vegetation, deep marsh vegetation, and submerged vegetation. The combination of these different vegetation types stabilizes the marsh soil, slows down flow, and promotes UV exposure in open water areas. The flow of water from the inlet zone into the macrophyte zone is carefully controlled with a bypass channel so as to prevent scour of marsh vegetation and soil.[33]

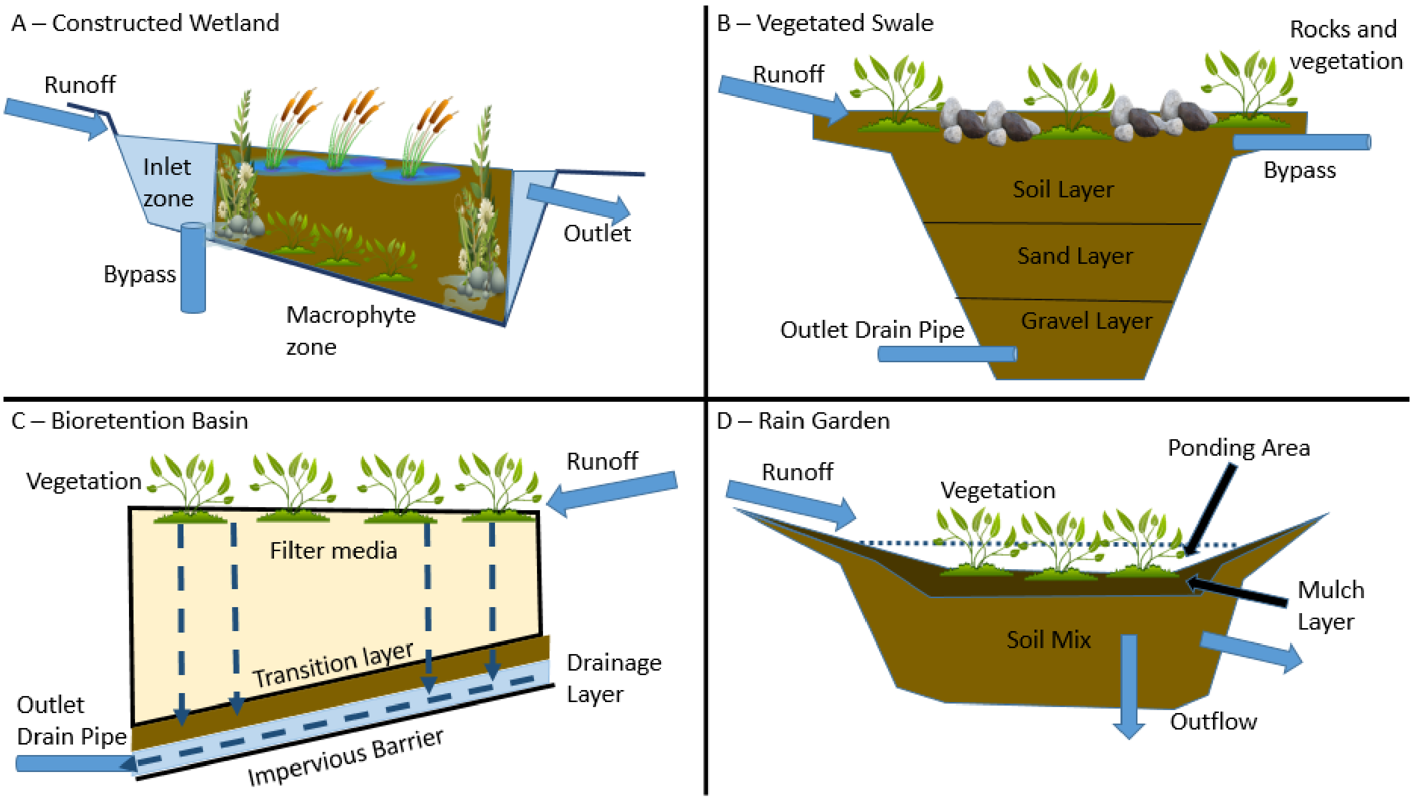



Figure 3: Select Green Infrastructure Example. A) Constructed Wetland. B) Vegetated Swale. C) Bioretention Basin. D) Rain Garden.

Pollutant removal in constructed wetlands occurs in several stages: settling, vegetation uptake, adsorption, filtration, and biological decomposition. Wetland-specific vegetation promotes a high degree of settling because it reduces water flow. Plants take up a great deal of the excess N and P contained in stormwater, filter other pollutants through their roots, stems, and leaves, and promote the growth of biofilms (thin films of bacteria colonies) that can also assimilate dissolved nutrients from the water.[34]

In addition to acting as a natural filter for stormwater, constructed wetlands are proven to be effective at controlling stormwater flows via infiltration, evaporation, and retention. Infiltration is the smallest contributor to reducing stormwater flow since wetlands areas are characterized by saturated soils. But effective wetland design can dramatically increase the time stormwater spends in the wetland, promoting evaporation and slowing release into local surface water bodies.[35]

***Vegetated Swales and Bioretention Basins***

Vegetated swales (Figure 3B) are excavated trenches that are filled with layers of porous media to create a shallow channel and covered with vegetation on the slopes and/or the top layer. The primary purpose of channelized swale design is to disconnect impervious surfaces from downstream surface water bodies. In this way, it slows down stormwater and acts as a filter for any pollution contained in it. A typical vegetated swale has a layer of gravel in which a drain pipe is placed, overlaid by layers of sand and soil, and topped with small rocks and vegetation. A bypass is often installed so as not to overtax the system during high flow events. The parabolic or trapezoidal shape of the swale allows for coarse and medium sized sediments to settle out, while the vegetation and microbes in the soil remove finer materials and associated pollutants through filtration, infiltration, adsorption, and biological uptake. Vegetated swales are highly effective for areas such as road medians, parking lots, and parks or recreation areas where flow is low and infrequent. They are green alternatives to traditional curb and gutter installations.[36]

Bioretention basins (Figure 3C) are similar to vegetated swales in their use of vegetation. However these basins have a critical difference to the vegetated swales: they are designed to pool water on the surface and then promote infiltration and percolation through filter media. The vegetation slows down the stormwater, enhances infiltration and maintains filter media porosity. These media typically consist of three layers: filter media layer, transition layer, and drainage layer. The filter media layers usually coarse sand or fine gravel, with grain size ranging from one to five millimeters. Below the filter media, water moves through the transition layers (which is designed to prevent downward migration of filter media) into the drainage layer, where it enters a perforated pipe connected to a stormwater drain. In some cases the drainage layers sits atop an impervious barrier to ensure that water enters the drainage system. Similar to vegetated swales and constructed wetlands, bioretention basins limit stormwater runoff and act as natural filters for any pollutants it contains. The primary method for limiting stormwater runoff is by retention by vegetation and soil moisture. Because of this, they are also limited to smaller scale usage like vegetated swales.[37]

***Green Roofs***

Green roofs are structures that are covered with growing media and vegetation that enable rainfall infiltration and evapotranspiration of stored water.[38] They consist of a waterproof membrane at their base, a growing medium, and vegetation. Water that falls on the roof infiltrates into the soil where it is held until it is either taking up by plants or evaporates. Overflow drains ensure that the roof doesn't become overloaded in high precipitation events. Effectively designed green roofs significantly reduce the amount of stormwater runoff that would otherwise runoff an impervious roof surface, even reducing stormflow by up 65% and increasing the time it takes for water to flow from the surface to a sewer by up to three hours.[39] Additional environmental benefits include providing habitat for local wildlife and increasing biodiversity, limiting the effects of the urban heat island, reducing energy costs, improving air quality in the surrounding area, and increasing the longevity of roof structures.[40] It is important to note that not all buildings are suitable for green roofs. Structures with a green roof must be able to withstand the extra load brought about by the soil, vegetation, and water.[41]

***Rain Gardens***

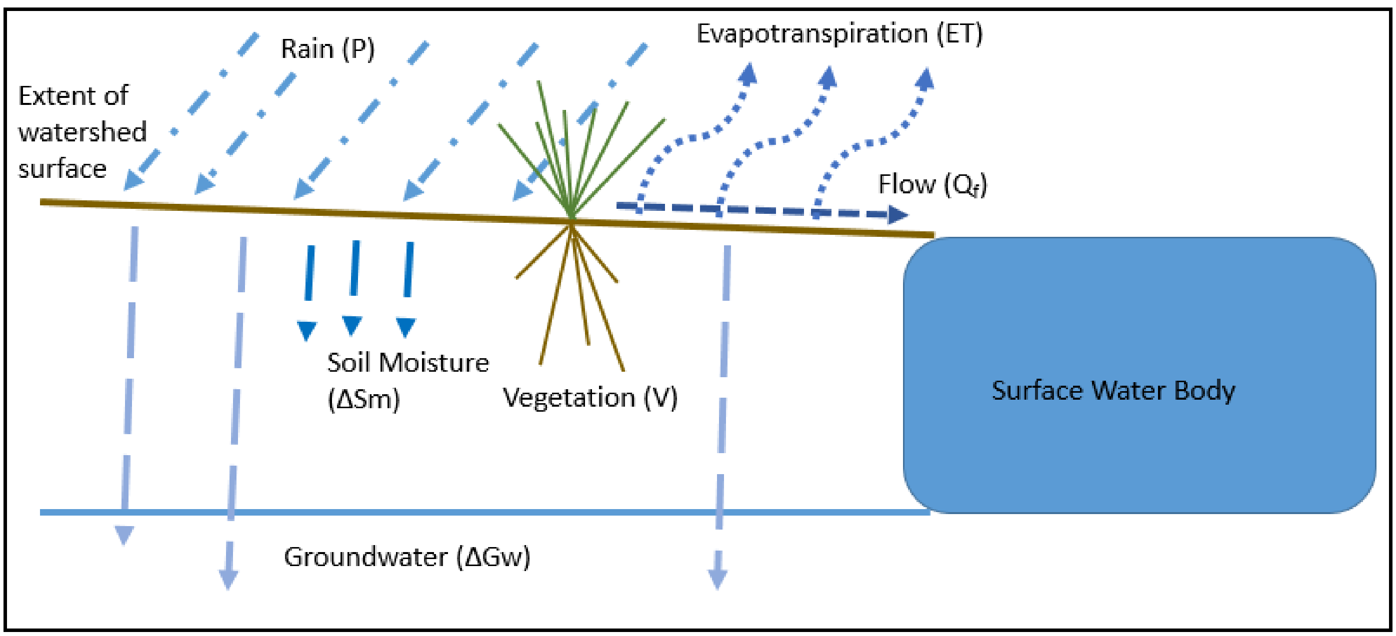
Rain gardens (Figure 3D) function similar to vegetated swales and bioretention basins in that they are designed to slow the movement of stormwater and provide natural filtration of contaminants.[42] They are formally defined as shallow vegetated basins that collect and absorb runoff from rooftops, sidewalks, and streets. Rain gardens collect runoff in depressions called ponding areas. These depressions are typically planted with vegetation that thrive in saturated soils. A mulch layer promotes retention of stormwater without scouring plants and washing away soil. Beneath the mulch layer is a soil mixture of sand and organic matter that is designed to promote infiltration and subsurface flow. Rain gardens mimic natural hydrology by promoting evapotranspiration in the ponding area and infiltration through the mulch and soil layers.[43] These features are becoming increasingly popular with homeowners because they offer stormwater management while increasing the aesthetic appeal of a landscape. Parking lots and urban parks are also excellent locations for rain gardens.[44]

***Permeable Pavements***

Permeable pavements are another green infrastructure technique used to catch rainwater where it falls instead of moving it through a piped system. Unlike traditional impermeable pavements, permeable pavements behave more like natural systems that allow for the infiltration and possible treatment rainwater.[45] A permeable pavement system typically includes an engineered porous urban surface composed of pavers, concrete, or asphalt and an underlying stone reservoir. The permeable layer allows for surface water to infiltrate instead of runoff, and the stone reservoir allows the water to slowly infiltrate into adjacent soil or to discharge via a drain system.[46] Such systems have proven effective in reestablishing more natural hydrologic balances by reducing runoff volume and slowly releasing water into the ground. They also reduce concentrations of some pollutants by physically trapping them in pore space in the pavement or soil below and biodegrading contaminants via the bacteria and plants living in the system. Additionally, because of the above positive controls on stormwater, permeable pavement systems can reduce the need for larger regional stormwater management systems.[47]

**Modelling Stormwater Runoff**

Rudimentary stormwater runoff models can be generated and used by high school students to study how land cover and other factors impact the flow of stormwater in different areas. Figure 4 provides a visual demonstration and associated mathematical expression of a basic stormwater runoff model based on six simple variables.




$$Q_f = P - (\Delta Sm + \Delta Gw + ET + V)$$

Figure 4: Simple Stormwater Runoff Model for Student Use[48]

In this rudimentary model, surface runoff flow ($Q_f$) is equal to precipitation (P) minus losses to soil moisture (ΔSm), groundwater (ΔGw), evaporation and transpiration (ET), and absorption by vegetation (V). Such models offer an opportunity for students to isolate variables and determine the impact of specific management practices, which are discussed in detail below. For instance, in an area that has 100% impervious surface cover, is essentially equal to P. As impervious surface cover decreases, so does surface runoff flow. Water is absorbed into the soil, some of which will infiltrate and reach the groundwater. Some will be absorbed by plants, and some will be lost to evaporation and transpiration. Using simple math along with climate data and simple approximations for infiltration and vegetation, students can easily determine the impact of reducing impervious surface cover and/or using one or more of the green infrastructure techniques presented below. For instance, if impervious surface cover is reduced to 50%, then $Q_f$ is equal to 0.5P – [0.5P – (ΔSm + ΔGw + ET + V)].[49] Other more complex variations can be introduced, like parceling out the watershed area into regions with different soil types that influence losses to soil moisture and groundwater, specifying vegetation types and amounts, and using local climate variation to modify evapotranspiration rates over seasons and time.

**Stormwater Flooding in Delaware**

Of critical importance to this unit is how stormwater runoff impacts my school community. Specifically, this unit focuses on the Route 9 corridor between New Castle and Wilmington, Delaware. Just south of New Castle, Route 9 is known as River Road (see Figures 2A and 2B above). River Road is bordered by the Delaware River to the east and marshland to the west. The areas around the road used to be marshland as well but were long ago filled in and developed. The proximity to the river and marsh is a frequent source of flooding on this specific stretch of road. In addition to frustrating residents and businesses along Route 9, this routine flooding poses a significant public safety threat because the road is designated as an emergency evacuation route. The primary existing flood control method involves the use of curbs and storm sewers designed to channel water away from the road into an adjacent wetland. This corridor has yet to receive any local, state, or federal funding for the construction of any green infrastructure, though it seems to be a prime candidate for bioretention basins, vegetated swales, and possibly an expansion of existing wetlands, which are most effective when they are present throughout the drainage system.

To the north in Southbridge, a similar confluence of river and marshland poses a significant problem during rain events and at high tide. Here, residents have developed their own methods of dealing with the chronic flooding, such as covering their basement floors with gravel and having elevated storage spaces. More formal measures have been taken by the city, including frequently de-clogging storm sewer lines and clearing a large drainage ditch of debris.[50] However, given the specter of rising sea levels due to climate change compounded with the already existing flooding issues, Southbridge is in need of a major overhaul to its stormwater management system. A major step towards more effective management of stormwater was proposed in 2014, when the Department of Natural Resources and Environmental Control proposed the construction of an urban wetland to act as a sponge during storms and high tide events. The project, known as the South Wilmington Wetlands Park, recently broke ground in the summer of 2019 and is expected to provide significant flood relief for the neighborhood.[51] The project's chief goal is to reduce flooding in the neighborhood by rerouting stormwater from the streets into the wetland.[52] Part of this involves separating the antiquated combined sewer system into stormwater and sewer pipes. The stormwater pipes will convey stormwater off the street into the wetland through a subsurface system. In addition to mitigating the flood risk from surface runoff, the wetland will also serve to increase regions resiliency against extreme high tides, storm surge, and rising sea levels. The wetland will also partially restore habitat for a variety of fish, aquatic, and wetland species. It will also provide recreational opportunities and green space to a neighborhood sorely lacking in those attributes.[53] However, without further deployment of green infrastructure that reduces the amount of stormwater running off into the wetland and adjacent river, this feature may have a limited impact on ameliorating the problem of routine flooding in the area.

## Strategies

In order to instill in students that science is not merely a body of isolated facts but a systematic process for acquiring new knowledge, I always try to incorporate real aspects of the scientific process into the classroom. The National Research Council (NRC) lays out a framework for how to ensure that under the Next Generation Science Standards (NGSS) students have authentic scientific experiences in their classrooms even as they learn the bodies of knowledge of the specific sciences. When implemented properly, this framework of "supports a better understanding of how scientific knowledge is produced and how engineering solutions are produced…help[ing] students become more critical consumers of scientific information."[54] This focus on process, according to the NRC, improves upon previous practices that reduced scientific procedures to isolated aims of instruction, rather than a vehicle for developing a meaningful understanding of the true scientific concept.

The central aspect of the NGSS paradigm that allows for this shift grounded in providing students with authentic science experiences for students. This is achieved by teachers implementing Science and Engineering Practices (SEPs). The eight SEPs are designed to model the scientific inquiry process from questions to conclusions, and represent a multitude of opportunities to engage students in exciting and relevant learning. This process of engaging in authentic science aids students in developing the types of critical thinking necessary to understand why the right is answer is right, and perhaps more importantly, why the wrong answer is wrong. Another critical aspect of the NGSS framework is providing students with the opportunity to use common language and to recognize connections and bridge disciplinary boundaries. To that end, teachers use the Cross Cutting Concepts (CCCs) to provide this context for student learning and empower them to deepen their understanding and develop a coherent and scientifically based view of the world.[55]

This emphasis on developing a strong evidence foundation supports student understanding of fundamentals of scientific truths instead of the traditional model of asking for rote memorization of facts that didn't serve students well in their post-secondary education or in the workforce. In fact, the NRC designed the NGSS model with this specifically in mind, citing that in the past "rather than learning how to think scientifically, students [were] generally being told about science and asked to remember facts," whereas the new standards focus on student understanding by "linking concepts and practices that build coherently over time throughout K–12, thereby helping to ensure that students who meet the NGSS will be prepared to succeed in science courses in both 2- and 4-year institutions."[56] The presentation of content in this unit is phenomena-based, another hallmark of NGSS that helps students deepen their content understanding. In this unit, I make use of a blended learning and a flipped classroom, hands-on learning, and the critical and higher order thinking in order to engage students in the content presented above.

### Blended Learning and the Flipped Classroom

Because I have so much material to cover in advance of the AP exam I don't dedicate much class time to lecture or direct instruction. Instead, I expect students to come to class with a certain level of background information that prepares them for hands-on and application based learning in the classroom. This background information comes from reading sections in our course textbook, watching Bozeman Science videos, reading articles from local newspapers, or other digital resources. This model frees up time in class to be spent on authentic science experiences through lab experiments, collaborative learning, and peer review.

Effectively using this model requires a great deal of advanced planning and buy-in from students and parents. It involves more than just assigning readings and expecting students to complete them. Students need to find value in the at-home assignments and then be held accountable for completing them. In order to promote engagement with these do-it-yourself materials, I have use daily quizzes based on the previous night's material. I allow students to use their notes and annotations to my outlines on these quizzes. For highly motivated students, this strategy works well. Less intrinsically-motived students often struggle early on with this model until they begin to see the value in coming to class prepared.

**Hands on Learning through NGSS**

In my classroom, I act as more a facilitator of learning than a source of information and correct answers. To that end, my teaching toolkit is full of strategies that get students *doing* science rather than *learning* science. I use a wide range of the NGSS SEPs in my classroom. In this specific unit, I will ask students to obtain and evaluate information, plan and conduct investigations, develop and use models, analyze and interpret data, construct explanations, and use mathematical thinking. In order to provide proper context for their learning, students use the following (CCCs) in this unit: systems and system models, cause and effect, and structure and function. As outlined in the activities section below, students will obtain evaluate information through close reading about stormwater management techniques. They will use a rudimentary stormwater model and mathematical thinking to study the immediate school area, and analyze and interpret the data they get from those models. Students then use these same practices to study Southbridge and the Route 9 Corridor, ultimately submitting a stormwater management plan based on their investigation, modelling, and analysis. The specific standards addressed can be found in Appendix A: Implementing District Standards.

The biggest challenge I find when employing the SEPs is wanting to interject. But it is important for me to limit my interruptions and let students struggle and find solutions. Like with the blending learning and flipped classroom model, the NGSS approach has to be carefully managed and not every student is going to be successful right away. But by not giving in to student demands and providing answers right away, I hope to train them to think creatively, work together, and develop their scientific "muscles" for use on the AP exam in May.

**Collaborative Learning**

I use collaborative learning for two reasons: to foster a sense of community in my classroom and because studies show that peers teaching and learning from one another to be highly effective. Collaboration and group work, whether in pairs, small groups, or more complicated jigsaw groups, is a staple in my classroom. It leads to development of high order thinking and communication, self-management, and leadership skills. It also allows me to meet with more students in less time to check for common misunderstandings and provide immediate feedback. Working collaboratively allows exposes students to diverse perspectives and prepares them for real life social and employment scenarios.

**FRQ Notebooks**

The AP ES exam consists of eighty multiple choice questions and three Free Response Questions (FRQs). Students get plenty of multiple choice practice throughout the year on quizzes and unit exams. In order to prepare students for the FRQs, I combine frequent low-stakes practice and high-quality peer and teacher feedback through the use of FRQ notebooks. Students keep a notebook for the duration of the year with each FRQ prompt, their response, and a scored rubric. For students, this is beneficial because they can track their progress throughout the year and use it as a study tool at the end of each unit and before the AP Exam. For me, these notebooks serve as key benchmark data for determining how much exam preparation each student needs, as well as strong evidence of understanding. I use a combination of released exam questions from College Board, my own written questions, and in some cases, student-generated prompts. These questions ask students to integrate knowledge from different aspects of the course in order to assess their understanding of key course content. They require students to think critically, make determinations of cause and effect, identify patterns, analyze relationships, complete mathematical calculations, and propose and justify solutions. They are the ultimate combination of NGSS SEPs and CCCs.

## Classroom Activities

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### Close Reading and Annotating Text

Students engage in a close reading of text excerpts on the EPA website for each of the following topics: stormwater runoff,[57] gray infrastructure,[58] environmental impacts of stormwater runoff, green infrastructure basics[59] and examples.[60] As they close read, students will annotate the text with a specific focus each time. Students annotate by hand or by using a software program or browser extension such as Kami. In the first read, students focus on the "what" of the content and identify key vocabulary for each topic. In their second read, students turn their focus to the "how" of the content, focusing on the processes involved in each stormwater management technique and continue their annotation. In their third and final read, students focus their attention to the "when" of the content and complete their annotation. This assignment is one that students complete independently ahead of class using Schoology. Students are given a reading quiz to check their understanding and can use their notes from the close read as an aid.

### Using Stormwater Models

Students use the stormwater runoff model from Figure 4 to study the impact of various management strategies and geographic conditions. The first tasks that students complete in this activity is to use a high resolution satellite image of the school property and surrounding neighborhoods to determine the percent of impervious surface cover. To do this, students are given the image and transparent grid paper with one square centimeter grids. They shade in areas of impervious cover and then calculate the percentage by dividing the number of shaded grids by the total number of grids and multiplying by 100. An alternative method based in the online geographic information system ArcGIS can also be used in this step. First, students find the school on the map. Next they use the measure feature to determine the total area. Then they specifically measure the area of individual impervious surfaces using the same tool and add up the total. Finally, they divide the impervious area by the total area and multiply by 100 as above. This percentage is used to determine the area where $Q_f = P$, since all precipitation that lands on an impervious surface is assumed to runoff. The remaining area follows $Q_f = P - (\Delta Sm + \Delta Gw + ET + V)$. Students are given model data to determine the remaining variables and determine the baseline stormwater runoff. Then, students work in pairs to simulate the impact of specific green infrastructure techniques. This requires students to make judgements on decreases in impervious cover and changes to the remaining variables.

For all scenarios, the area of study totals 450,000 $m^2$ and receives 4 cm of rainfall in a 24-hour period (which represents a typical summer storm in our area). That means in all cases the total volume of P equals 18,000 $m^3$ . Model values for each variable are as follows: $\Delta Sm = 0.2P$, $\Delta Gw = .35P$, $ET = 0.05P$, and $V = 0.02P$. For the baseline scenario (where impervious cover is approximately 20%), the workflow looks like this: $Q_f = 0.2P + [0.8P – (0.2P + 0.35P + 0.05P + 0.02P)]$, and $Qf = 6{,}840\ m^3$ .

The scenarios that students groups are described below. For their assigned scenario, students must determine the reduction in impervious surface cover (if necessary), and make educated predictions on how the remaining variables are impacted by their change. By using the simulation at www.runoff.modelmywatershed.org, students can get reasonable values for each variable. Student Group A decides that a large grassy area adjacent to the school parking lot would be a good site for a large rain garden. Student Group B decides that a reasonable plan is to install permeable pavements on all roadways and parking lots in the study area. Student Group C decides that green roofs should be installed on all structures in the study area. Student Group D wants to install vegetated swales bordering all paved surfaces in the study area. If their scenario reduced the percentage of impervious surfaces (as in Student Groups B and C), students need to recalculate their initial coefficients as described in the Using Stormwater Models section above. Once students have altered all their variables to match their modification, they must calculate the value for $Q_f$ and determine the percent change between this value and the baseline value. Since each individual modification is likely to have a limited impact on reducing stormwater, students are tasked with using this information to quantify the impact of combining all of the treatments.

**Planning for Stormwater Management in Southbridge and the Route 9 Corridor**

In this activity, students use the knowledge from their stormwater modelling activity to develop a plan to manage the stormwater in the Southbridge neighborhood or along the Route 9 Corridor south of New Castle. Students are split into two groups, each tasked with studying one specific area. Since these groups are much larger than in the previous activity, each student must have one of the following specific roles: team leader, scientist(s), data processor, or communicator(s). The team leader is responsible for all communication with the teacher and moving the group along through each task. The scientist(s) is tasked with completing the scientific investigation (such as research into specific techniques, using ArcGIS, making predictions for specific variables in their model, etc. The data processor is tasked with using the information given to them by the scientist(s) to run the calculations in the stormwater model. The communicator(s) compiles the findings of the group and ultimately presents the findings of their group.

Students use www.modelmywatershed.org/analyze in a manner similar to the previous project to first determine the total area of study and impervious cover. By using the analysis features of this site, students can determine how much of the area is developed, what soil infiltration looks like, and mean sea level. They can then return to www.runoff.model.mywatershed.org to make educated predictions for values of ΔSm, ΔGw, ET, and V. They use the same rainfall event (4 cm in a 24-hour period) and their study area features to establish their baseline runoff data. Once their baseline is established, students can begin identifying areas where green infrastructure may reduce the environmental impacts of stormwater runoff. Students go through the same process from their previous activity to predict the impacts of specific treatments. In their planning, students are tasked with justifying their choices of treatments and where those treatments are located.

Once they have developed their plan, students can use the model feature of the site to test their plan's effectiveness in both reducing stormwater runoff volume and improving water quality. To do this, students must redefine their study area and then select "Model." They use the slide bar in the model to set precipitation to 4 cm. This provides a data set with values for $Q_f$, ET, and infiltration (a combination of ΔSw and ΔGw), and concentrations of total dissolved solids, nitrogen, and phosphorous. By selecting "add changes to this area, students can insert rain gardens, vegetated swales, porous paving, and green roofs to the area and re-run their model to determine the impact of those changes. This provides them with the evidence they need to argue for their changes. It also provides a check to their own model and an opportunity to make changes to their plan if necessary. By taking screenshots of the site and their calculations as they work, student groups can compile the necessary materials to make a detailed presentation of their plan to share with their larger class community.

**Answering and Scoring a Stormwater FRQ**

Students conclude this unit by answering an FRQ about stormwater management in Southbridge in their FRQ notebooks. For this activity, students answer a question written by me that is modelled on FRQ number 2 as described in the Course and Exam Description, which asks students to analyze an environmental problem and propose a solution. The prompt they answer appears below.

The South Wilmington Wetlands Park is an urban constructed wetland designed to absorb stormwater runoff from the Southbridge neighborhood in Wilmington, Delaware. It is currently under construction and will be completed by the end of 2021. Prior to the construction of the wetland, the area suffered from frequent flooding during rain events. Water pooled on the streets in low-lying area and storm drains that fed into the Christina River overflowed as the traditional gray infrastructure was overwhelmed. The graph below shows the change in impervious surface cover and stormwater runoff in the neighborhood from 2000 to 2025. The numbers for 2025 are projected values based on the installation of the wetland.

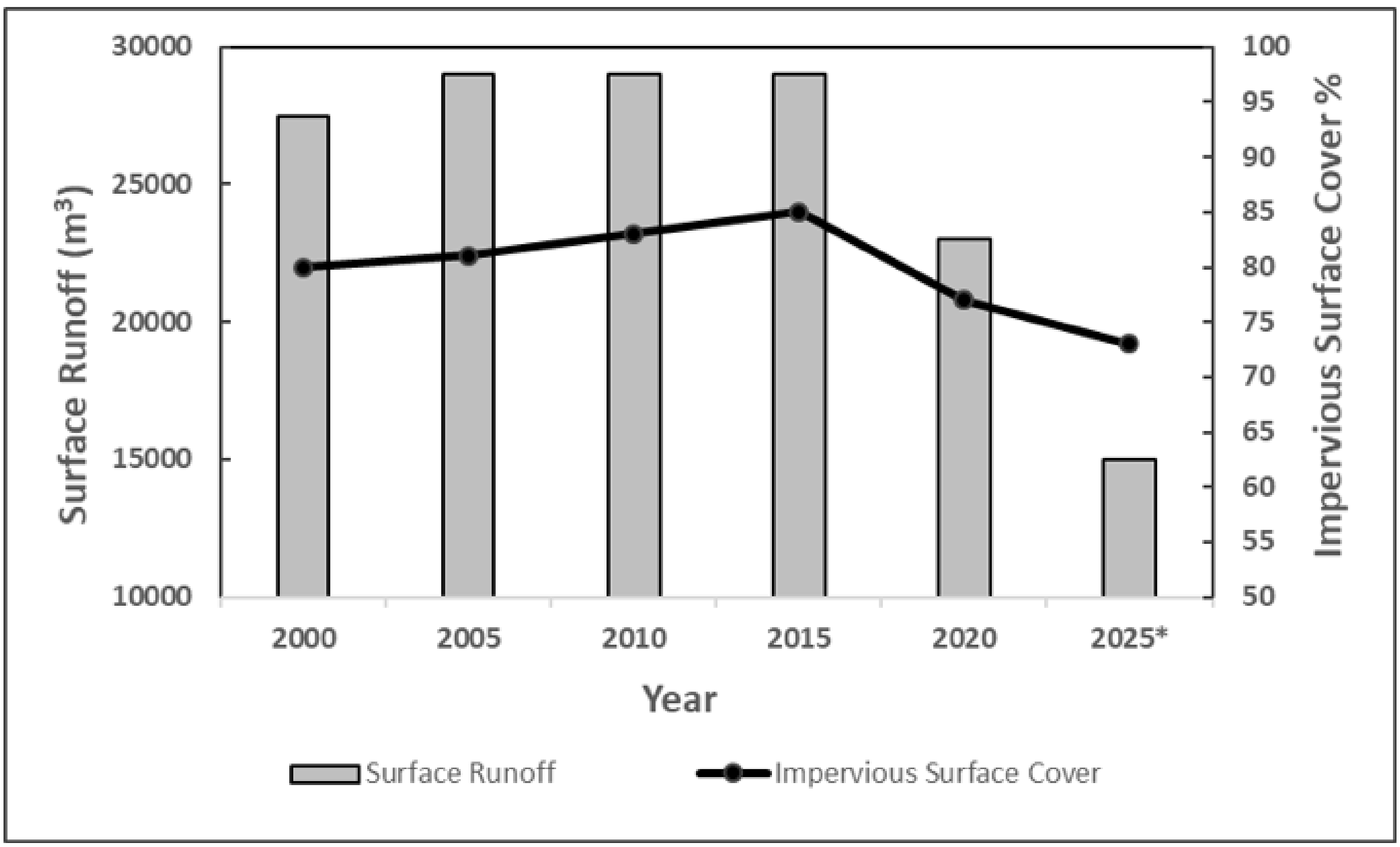


Figure 5: Simulated Runoff and Impervious Surface Cover for Southbridge, Wilmington, Delaware.

1. Calculate the projected percentage change in stormwater runoff from 2000 to 2025. You must show all work to earn credit.

2. Define gray infrastructure and identify two negative environmental consequences it has.
3. Describe how a constructed wetland, such as the one being built in Southbridge, reduces the negative impacts of stormwater runoff.
4. Define green infrastructure and explaining how it limits stormwater runoff.
5. Describe two green infrastructure (excluding constructed wetlands) techniques that could be used to further reduce stormwater runoff in the Southbridge neighborhood.

After answering the question in their FRQ notebooks, students are given a printout of the rubric to grade their response. Then they trade with a peer complete the scoring process. If there is a discrepancy between scores, I help students identify where they did and did not earn points. The rubric includes the question, a point value, and a description of the answer(s) that would earn them those points. A description of that rubric follows.

Part a is worth two points, one for a correct set up and one for the correct answer: $[(15000\ m^3 – 27500\ m^3) / 27500\ m^3] \times 100 = -45\%$. Part b is worth three points. One point is awarded for correctly defining gray infrastructure as being designed to move stormwater away from the built environment. One point each is awarded for correctly identifying an environmental consequence, including localizes flooding, erosion of stream banks, alteration of stream/river hydrology, and transfer of surface pollutants into local surface water bodies. Part c is worth one point for correctly describing at least one of the following: slowing the flow of stormwater into local streams or rivers, promoting infiltration and groundwater recharge, naturally filtering out suspended solids, and biologically or chemically filtering out pollutants. Part d is worth two points, one for defining green infrastructure as being designed to mimic nature and capture rainwater where it falls, and one for explaining that it works by reducing, slowing, and filtering stormwater (must have all three to earn point). Part e is worth two points, one for each description of a green infrastructure technique, including vegetated swales, bioretention basins, green roofs, rain gardens, and permeable pavements.

## Appendix: Implementing District Standards

Students satisfy the following science practices as outlined by the College Board in the AP Environmental Science Course and Exam Description: explain environmental concepts, processes, and models presented in written format and propose and justify solutions to environmental problems. Students satisfy the first of those practices during the activity on using stormwater models and the second during the activity on planning stormwater management practices. Students satisfy both of these practices on the summative FRQ. I also use several broader practices laid out by the NGSS framework for learning, including the following SEPs: obtain, evaluate, and communicate information, develop and use models, analyze and interpret data, and construct explanations. Students use this combination of AP and NGSS practices to meet AP Environmental Science Learning Objectives EIN-2.M (describe the relationship between land use and flood risk) and STB-3.E (explain how the use of green infrastructure can reduce the risk of flooding during heavy rainfall events).

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## Endnotes

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[2] (US Global Change Research Program 2014)

[3] (Keller et al. 2017)

[4] (Mahmood et al. 2014)

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