Thermal Impact Assessment for Discharging Stormwater Runoff: Case Study

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Abstract
Discharge of sensible heat (temperature) into receiving streams is regulated under several provisions of Pa 25, which identify temperature as a water quality constituent and therefore discharges must comply with anti-degradation regulations. This presentation emphasizes streams designated as exceptional value in which temperature must be maintained and protected. The case study is stormwater thermal impact assessment for a proposed 96.6-acre site in Chester County, Pa. Little Valley Creek, an Exceptional Valley Stream, that bisects the site. The post-development site will have 22 drainage areas, several of which either will introduce new point discharge locations onto newly established or improved riparian zones.

Most stormwater BMPs are based on a conservative, and “closed” stormwater system. Consideration of thermal anti-degradation is unique from other regulated water quality criteria in that temperature is not a conservative water quality constituent and stormwater management infrastructure is a non-conservative, “open” thermal system. Thermal management of stormwater discharge requires control of heat flow from the “first flush” of stormwater before it reaches a stream. Both non-structural and structural thermal mitigation BMPs are proposed in this case study. A principal design considerations is the use of the earth acts as a “thermal sink”. Also, the presentation will outline thermal processes within select drainage areas which will be assembled, ordered, and discussed as “treatment trains”.

Introduction and Background Discussion

This paper concerns stormwater runoff thermal impacts on a stream at a Brownfield Redevelopment Site that is designated as an Exceptional Value (EV) stream. Dunne and Leopold (1978) documented that land use alterations such as proposed for the Site can impact short-term, and long-term, stream temperatures. Pennsylvania’s anti-degradation regulations, found at Title 25 PA Code, § 93.4a (d), (DEP, 2007) require, among other things, that the water quality of the receiving stream be maintained and protected. Thermal water quality is included in these water-quality regulations. Recent case law has defined that 25 PA Code, § 93.7, Table 3 must apply in preparing a Non-point Source Pollution Discharge Elimination System (NPDES) permit for a site with construction activity. The method to reach compliance with thermal anti-degradation is to consider “Maximum temperatures in the receiving water body resulting from heated waste sources regulated under § 93, and § 96 and other sources where temperature limits are necessary to protect designated and existing uses.” This applies to streams designated “Special Protection” Waters of the Commonwealth, which includes EV streams. More specifically the temperature criterion is “thermal discharges may not result in a temperature change in the receiving water body by more than 2°F during a 1-hour period.”
The reference cited above in § 93.7 to “heated waste sources” suggests that the original intent of the regulation was to control thermal discharges of residual heat discharges from industrial processes. For such purposes the design calculations to meet the “2°F during a 1-hour period” criterion is a direct mixing calculation of thermal discharge rate and the minimum flow condition and ambient temperature in the receiving stream. An accurate design calculation that defines thermal anti-degradation criterion to the thermal impact of stormwater runoff for a development site is a much more complex. It involves determining cross terms between design weather events (which is random) and an assembly dynamic, time dependent, heat transfer processes (including convection, conduction, radiative heat transfer) in a highly heterogeneous setting. Furthermore, although stormwater fluid volume conveyance can be considered conservative, the entire stormwater conveyance system is non-conservative because it is an open heat transfer system. There are few qualitative references in the general stormwater management literature which describe the relative advantages and disadvantages of various stormwater BMPs in mitigating thermal runoff.

Figure 1. Site location (See Arrow Below)

As quantitative analysis of the thermal controls on thermal impacts from storm water runoff is very complex and would require computer models. The development of such thermal runoff models is currently in the research and development stages (Rao-Espinosa, and others, 2001; Kieser and others, 2001). As for the historical development of stormwater runoff equations, one can eventually imagine global formulas for planning and application purposes will result. Eventually, with large scale field data collection efforts to account for thermal exchanges at surface interfaces, and heat transfer between the land surface and runoff it will be possible to estimate thermal impacts more accurately. Field research is needed.

Site Location and Description of Present and Improved Stream Corridor

The Site is an 86 acre Brownfield Redevelopment Project (BRP) which is the former location of the Worthington Steel Plant, located in East Whiteland Township, Chester County, PA (Site). The setting is mixed residential, commercial, and industrial land use. The setting is suburban, several miles west of

1Although not addressed in PADEP’s December 30, 2006 BMP Manual, impacts associated with stormwater “first flush” have been presented in PADEP’s BMP Stormwater Management Workshops in 2007.
Philadelphia near US Rt. 202 and Rt. 29, and is short distances of major arteries which lend easy access to the Washington D.C-Boston population centers and the northeastern-US regional corridor.

The bedrock geology at the Site is entirely comprised of Conestoga Formation. This formation is typically composed of an impure limestone. The bedrock/soil interface is characterized by pinnacles and numerous quartz veins (PA GS, 1982). A Site geotechnical investigation using more than 200 borings concluded infiltrating stormwater throughout much of the Site would pose unacceptably high risk of sinkhole formation (Earth Engineering Incorporated, 2007). Risk of sinkholes was an important constraint in the selection of suitable areas for infiltration BMPs.

At the present Site there is an 850-foot length of stream channel in a buried culvert that discharges to a deeply incised, unstable channel, which then flows to the downstream boundary of the property. The culvert and incised channel are designated Little Valley Creek (LVC) reach 806 (Chester Co., 2004). The total upstream drainage area, which contributes to flow in LVC at the downstream boundary, is 1,450 acres (Momenee & Assoc., Inc.)

Figure 2. Present Surface above culverted stream

Figure 3. Culverted stream outlet

The Site is entirely located within the Little Valley Creek (LVC) watershed. LVC is a second order tributary to Valley Creek, which is a third order tributary to the Schuylkill River; a major regional tributary river that flows into the Delaware River in Southeastern PA. LVC flows from the west to east across the Site and partitions it (Figure 4). The largest portion of the stormwater runoff from the Site drains northerly towards LVC, and smaller portion drains southerly to LVC.

The project redevelopment plan proposes to “daylight” the culvert and construct a scientifically designed stream channel and riparian corridor as part of the design. A new 1,560 foot long meandering stream corridor will replace the existing culvert and incised stream channel and it will include stable channel & banks, and riparian buffers (Habitat by Design, 2007)(Figure 4).

Figure 4 also shows 22 stormwater runoff drainage areas, or sub-drainage areas, for the planned Site improvements. In Figure 4, disconnected areas which have the same color contribute to the drainage area. As an example, all drainage areas labeled “DA #4” and colored light blue indicates they are part of one drainage area. For some drainage areas more than one label is used in the figure for drainage area label, i.e. “DA #4/DA #3”. The second label indicates stormwater control for that drainage area is time dependent, and for purposes of this report only the initial drainage area designation is significant.
Figure 4 - Locations of site layout, drainage areas, and Little Valley Creek (scale not shown)
Thermal Impact Mitigation Principles

The newly revised NPDES permit application is not specific in its requirement for a “Thermal Impact Analysis” which leaves flexibility. The analysis can be a narrative analysis that is tempered and accompanied by descriptive quantitative analysis. Heat transfer principles were generally invoked in the discussion of the thermal mitigation BMP design in narrative analysis for the subject Site. Among these principles are;

- Thermal impacts of stormwater runoff are mitigated through heat transfer mechanisms including conduction, convection, and radiative transfer,
- Sensible heat transfer for stormwater flow occurs across all boundaries because the stormwater system is an open (non-adiabatic) system,
- Rate of heat transfer depends on temperature differences between objects,
- Phase transfers (vaporization; evapotranspiration) are also energy transfer mechanisms which have thermal impacts on stormwater,
- The control of thermal impacts from stormwater runoff is time dependent, which includes the entire period which controls the initial conditions for the storm event.

All these heat transfer processes can be used to create an energy budget for the entire Site, or just within a stream, such as LVC. A general equation that expresses this is;

\[ Q_o = Q_s - Q_r + Q_a - Q_{ar} + Q_v - Q_{bs} - Q_h - Q_w - Q_e \]  \( (1) \)

Where: \( Q_o \) = stored energy increase (sensible) in stream at the Site, and,

- \( Q_s \) = solar radiation incident at the water surface
- \( Q_r \) = reflected solar radiation
- \( Q_a \) = incoming long wave radiation from the atmosphere
- \( Q_{ar} \) = reflected long-wave radiation
- \( Q_v \) = net energy advected into the Little Valley Creek
- \( Q_{bs} \) = long-wave radiation emitted by the water
- \( Q_h \) = energy conducted from (to) water mass as sensible heat
- \( Q_w \) = energy advected by evaporated water
- \( Q_e \) = energy used in evaporation/transpiration, (Veissman, 1989).

The major component of concern here in the equation for thermal impacts on LVC is \( Q_v \). \( Q_v \) is the sensible heat in stormwater runoff itself both from on-site runoff and from upstream. The season for maximum thermal surface loading is the summer when solar radiative transfer is greatest, which in turn causes the largest enthalpic energy increases within the Site structures (the roof structures, the parking lots, sidewalks, etc.)
Because the heat transfer processes which thermally load the stormwater runoff from site structures are time-dependent, and proportional to the temperature difference between precipitation and heated surfaces, it is logical that stormwater runoff from the first part of the storm is weighed most for thermal impacts. As in other types of surface water quality impacts, the very first stormwater runoff, or the “first flush”, from a summer rain event is considered most thermally loaded (PADEP, 2007). This is defined as about equivalent to first half-inch (1/2-inch) of runoff. “First flush” is convertible to volume by multiplying precipitation depth over impervious surface. It is assumed here that only flows from impermeable, heated surfaces contribute to thermal “first flush” and that the first half-inch rainfall on vegetated surface does not contribute significant sensible heat runoff.

**Thermal Impacts on Little Valley Creek**

Although the LVC is a culverted, deeply channelized and unstable in much of the Site, it is designated an Exceptional Value (EV) stream. Pennsylvania’s anti-degradation regulations for this “special protection” designated in 25 PA Code, § 93.4a(d) require that the stream water quality is maintained and protected, and this includes thermal impacts (PADEP, 2007). The regulation is general and can apply to the water quality impact on the stream both during non-storm and storm events. For this discussion only thermal impacts are of concern, and “short-term” refers to a storm event period; “long-term” refers to non-storm event, baseflow conditions.

**Mitigation of Long-term Thermal Impacts**

Long-term impacts on thermal conditions of Little Valley Creek are principally derived from mechanisms that occur in the planned improvements to the stream channel and stream corridor during periods of baseflow conditions. Other Site changes and designs are assumed to have minimal thermal water quality impacts during these baseflow periods. Compared to present conditions at the Site, “daylighting” the stream culvert and improving the unstable stream reaches will improve surface hydrology. These thermal benefits are not quantifiable, but implied as a corollary benefit in the BMP Manual itself (DEP, 2006), which describes the benefits of removing culverted streams, or “stream daylighting.” It describes a culverted stream as,

> “. . . pipes *that (sic)* serve to convey water more rapidly than the original stream would have done, creating downstream flooding or surcharging of both the sub-surface culverts and surface outlets. Deprived of both oxygen and sunlight, the original rate and water quality buffering function of first and second-order streams has been lost.”

We can add that “daylighting” a culverted stream also restores several thermal advantages.

The scientific design of a natural channel and installation of a riparian buffer will provide thermal cooling benefits through several new mechanisms:

- The new designed channel will introduce riffles into flow reaches, which in turn will induce mechanical cooling of stream water,
The scientific design for the new stream corridor includes extensive plantings, which greatly expand evapotranspirative cooling,

- The installation of extensive tree plantings will create overbank stream shading within the “daylighted” stream reach will lessen the influx of solar energy into the water, and
- The stream bank restoration will remove assorted gullies which presently are located on the Site and which convey thermally loaded runoff into the storm runoff system or into LVC.

The stream channel and stream corridor improvements will introduce other thermal mitigation mechanisms caused by ground-water/surface water interactions. These include;

- The removal of damaged/failing storm sewer system which presently acts as subsurface drain and depletes the discharge of less thermally loaded baseflow, and
- The culvert removal will allow baseflow discharge to stream.

Guides to Mitigate Short-term Thermal Impacts in this Site and Examples

Regulatory procedure requires that the NPDES permit application include an evaluation of non-discharge alternatives. This means to consider stormwater management practices that are environmentally sound and cost-effective when compared with the environmental cost of the thermal degradation from unmitigated discharges. Operationally, this means the stormwater design evaluation should show that thermally loaded stormwater discharges into surface water in the EV watershed will use a combination of BMPs and treatments such that thermal conditions in the receiving stream will not degrade from existing EV conditions,

The thermal principles applied to the Site result in these guides for thermal mitigation:

- The temperature of heated stormwater is reduced by energy transfer to the earth “thermal sink”,
- The stormwater conveyance system itself permits heat transfer as an “open thermal system”,
- The thermal BMPs simultaneously can reduce sensible thermal content and serve as volume or peak discharge BMPs,
- Sequential BMPs can serve as a thermal mitigation “treatment train” over time and through the physical site,
- Thermal BMPs are both non-structural (passive) and structural (active), and
- Where it is necessary to discharge stormwater, the discharge locations should be distributed along the stream reach.

These guides are employed in the following design examples for the Site.

A. Maintain the Stormwater on Site.
Thermal impact analysis for drainage areas becomes moot where runoff remains on site. This happens if none of the thermal content of heated summer stormwater can reach the EV stream but is reused through irrigation reuse or infiltration. For the Site, onsite reuse of water during the summer for some areas alternates with infiltration on site during the winter. Reuse is only
important as thermal control during the irrigation season. As an example, both these methods are used for stormwater runoff management from the five areas which contribute to Drainage Area No. 4 (DA #4) (see figure 4). DA #4 is 14.05 acres and includes the rooftops of four large buildings, portions of road surfaces, and the area around storm-water management basin No. 4 (SWMB #4). “First Flush” runoff from these impermeable surfaces amounts to 15,036 cf. volume, which collects in subgrade rain harvesting tanks, is conveyed through water quality structures and pipes, then to SWMB #4, which has a 114,220 cf. volume capacity. The stormwater is pumped from the wetbasin for reuse during summer irrigation season or pumped to an infiltration trench field in the southeastern part of the Site during the remainder of the year.

B. Size the BMP to the “First Flush” Volume
This strategy assumes the thermal content of the “first flush” is mitigated using a BMP which has a thermal mitigation volume on the same scale. As an example, Bioretention Drainage Area #2 (BR #2) is a 3.61 drainage area which demonstrates this approach. BR #2 has a “first flush” volume of 4,225 cf. It includes portions of roadways, walks, and parking lot east of Building R-5, and is located in the north central area of the Site (Figure 5). As Stormwater Runoff is collected and conveyed in stormdrains, thermal mitigation begins through heat exchange with the storm pipes and a sub-surface water-quality management system (Figure 6).

![Fig. 5 – View of BR #2 drainage area.](image1)

![Fig. 6. - Schematic BR #2 thermal treatment train.](image2)

The volume in BR #2 drainage area flows by gravity northward towards the southern bank of Little Valley Creek and discharges into Bioretention Bed #2 (Figure 6). The Bioretention Bed supports a vegetation growth that assists in the volume uptake of the thermally loaded water by evapotranspirative cooling and infiltration below. The volume capacity of BR #2 is 11,553 cf., more than BR #2 “first flush” volume. BR #2 is designed primarily for Stormwater volume control not thermal mitigation, although it serves both purposes. In addition, upon reaching capacity BR #2 control is designed to divert excess volume across a swale onto the riparian buffer along the southern bank of LCV. Close direct contact of the stormwater with riparian surface vegetation is also a highly effect thermal mitigation BMP.
C. Use Non-Structural (Passive) Elements in the Thermal Mitigation.

Non-structural elements are demonstrated for the 3.52 acre Drainage Area #7 (DA #7). DA #7 is located in the southeast corner of the Town Center (Figure 7). It includes portions of the parking areas, adjacent roadways, rooftop areas and associated walks and the clubhouse. The non-structural BMP “treatment train” begins before a storm event by employing passive designs. The non-structural BMPs effectively lessen the initial heat in the Site by various means, like establishing shade over impermeable surfaces through landscaping and plantings. Vegetative matter minimizes the absorption of radiative heat before a summer storm and is a source of evapotranspirative cooling (Figure 8).

D. Customize a Thermal Mitigation BMP Using a Heat Transfer Exchange Design.

DA #7 also includes a heat exchanger design element. The “first flush” volume in DA #7 is 5,452 cf. which is collected and conveyed by gravity via a series of storm inlets and piping, through a Subsurface Water Quality System. As before, advective/conductive heat exchange begins mitigating temperature occurs during conveyance. Residual sensible heat is further mitigated in SWMS #7, a 12,763-cf. unit.

Fig. 7 – Layout of Drainage Area #7.               Fig. 8. - Schematic DA #7 thermal BMPs

SWMS #7 is a custom designed BMP which serves both as a peak discharge control and thermal control. It is a large, sub-grade unit that contains overhead baffles that distribute entering stormwater over a rockbed made of washed stone. Flow percolates over the washed stones, which is an ideal design for maximizing contact on the heat exchange surfaces. The rocks have a large heat capacity and initially are at “earth sink” temperature. Once down though the rock bed, water collects along the sloped bottom of the unit and flows to a discharge pipe. Outflow discharges from SWMS #7 by gravity to level spreader onto south bank of riparian zone.

Summary

Pennsylvania’s anti-degradation regulations require maintenance and protection of the thermal water quality of special protection streams. During storm conditions, the proposed BMP
“treatment train” of non-structural and structural BMPs, as well as a restored stream channel, will mitigate potential impacts to Little Valley Creek from “first flush” thermal loading generated by stormwater runoff from the Site. The BMPs will utilize a variety of thermal mitigation mechanisms – including thermal exchange with “thermal sinks” through infiltration and heat losses in underground structures, thermal exchange during conveyance and discharge through riparian zones, and reuse of stormwater. In addition, the Site will actually improve the thermal water quality conditions of Little Valley Creek during non-storm baseflow conditions. These improvements will occur because of restoration of the stream and riparian buffer zones and removal of several existing conditions at this Brownfield Site. These include removal of leaky storm drains which deplete baseflow and elevate stream temperature during baseflow conditions.

References

Chester Co. Water Authority and others, July 2004, Valley Creek Technical Compendium.


Earth Engineering Incorporated, 2006, Geotechnical Reports for the Worthington Redevelopment Project Site (various).


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