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A storm event-based approach to TMDL development

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Abstract It is vitally important to define the critical condition for a receiving water body in the total maximum daily load (TMDL) development process. One of the major disadvantages of using a continuous simulation approach is that there is no guarantee that the most critical condition will be covered within the subjectively selected representative hydrologic period, which is usually several years depending on the availability of data. Another limitation of the continuous simulation approach, compared to a design storm approach, is the lack of an estimate of the risk involved. Because of the above limitations, a storm event-based critical flow-storm (CFS) approach was previously developed to explicitly address the critical condition as a combination of a prescribed stream flow and a storm event of certain magnitude, both having a certain frequency of occurrence and when combined, would create a critical condition. The CFS approach was tested successfully in a TMDL study for Muddy Creek in Virginia. The present paper reports results of a comparative study on the applicability of the CFS approach in Taiwan. The Dy-yu creek watershed in northern Taiwan differs significantly from Muddy Creek in terms of climate, hydrology, terrain, and other characteristics. Results show that the critical condition for different watersheds might be also different, and that the CFS approach could clearly define that critical condition and should be considered as an alternative method for TMDL development to a continuous simulation approach.

Keywords Critical flow-storm (CFS) approach · TMDL · BASINS/WinHSPF

Introduction

The TMDL process is one in which water quality conditions in impaired water bodies are mitigated by controlling watershed pollutant loads from point and nonpoint sources (NPS). Point source pollutants are identifiable inputs of waste that are discharged via pipes or drains primarily (but not exclusively) from industrial facilities and municipal treatment plants into rivers, lakes, and ocean. Besides, nonpoint source (NPS) pollution occurs when rainfall, snowmelt, or irrigation runs

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over land or through the ground, picks up pollutants, and deposits them into rivers, lakes, and coastal waters or introduces them into ground water. According to USEPA TMDL guidelines, in calculating the total allowable pollutant load, a "critical condition" in terms of hydrologic variables such as precipitation and streamflow should be considered (40 CFR 130.7(c)(l)).[1] However, most TMDL developments completed to date have been based on continuous simulation modeling analyses using data collected for a specific period, usually several years. The critical conditions are not defined in the continuous simulation approach, but are taken as the "worst conditions" obtained from the continuous simulation results.

Theoretically, if the period of modeling is sufficiently long, the critical condition for the receiving water body in question might be captured. However, there is no guarantee that it will catch the most limiting condition during a selected period of time, which normally is selected due to the availability of data. In contrast, the proposed storm event-based critical flow-storm (CFS) approach (Zhang 2000) explicitly addresses various factors that contribute to the occurrence of the critical condition so that a reasonable estimate of such a condition could be made. Therefore, the CFS approach fulfills one important requirement, i.e., defining the critical condition, in the TMDL development.

Introduction of the storm event-based CFS approach

Under the CFS approach to developing a TMDL, a critical condition is defined as the combination of stream flow, magnitude of the storm event, and an appropriate set of initial conditions of the watershed in question. The CFS is an event-based approach, in which only a limited number of storm events need to be simulated. A graphic representation of the CFS approach is given in Fig. 1.

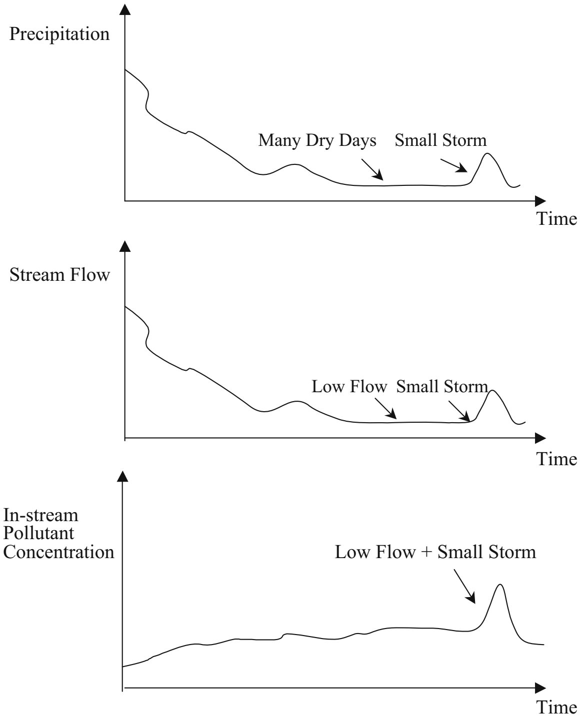

Fig. 1 Graphic representation of the CFS approach

In general, most TMDLs have been developed using continuous simulations that require extensive data for preferably a long period of time, which may or may not have covered critical conditions. The CFS approach tries to define a critical condition, which is a combination of a low flow in the stream and a storm event with a relatively small return period. Therefore, the CFS approach to the TMDL development would relax the need for long-term, continuous data, especially on water quality, which usually are more limited.

The control strategy for an impaired water body is normally a combination of point source controls and best management practices (BMPs) for reducing nonpoint source loads (Culver et al. 2002). The purpose of calculating the joint return period for a specific flow rate combined with a certain magnitude of a storm event is to estimate the risk of water quality impairment associated with the selected allocation scenario. For example, the return period of the low flows averaged over a period of 30 consecutive days that can be statistically expected to occur once every 5 years, i.e., 30Q5, with the concurrence of a 1.0-in. storm

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[1] Section 130.7 "Total maximum daily loads (TMDL) and individual water quality-based effluent limitations, TITLE 40 "Protection of Environment", Code of Federal Regulations.

was estimated as 30 years. By the same token, the risks associated with various combinations of a low flow with a certain storm event can be readily estimated by using, for example, the Binomial principle.

Traditionally, design approaches for achieving water quality goals by controlling point and nonpoint source of pollution are usually achieved separately. For point sources, a certain low flow is commonly designated for point source wasteload allocations under the National Pollutant Discharge Elimination System (NPDES) program. As for nonpoint source control, the design storm concept is generally applied for implementing BMPs. A design storm is a precipitation pattern defined for use in the design of a hydrologic system. Design storm can be based upon historical precipitation data at a site or can be constructed using the general characteristics of precipitation in the surrounding region (Chow et al. 1988). Traditionally, a storm with a large return period, e.g., 100 years, is selected in flood control design. As for water quality control, if selecting a large storm (i.e., 2.5-in. or 3.0-in.), which corresponds to a longer return period, a more stringent control strategy is required and, thus, more protection of water quality because of less risk of violation. However, smaller- to medium-sized storms are far more important with respect to water quality than those quite large storms (Nehrke and Roesner 2004). Due to resource limitations and cost, building smaller-sized BMPs is more practical in watershed management. The placement of many smaller-sized BMPs at different locations in a watershed may be a more cost-effective approach than installing a large, end-of-pipe type of BMP in controlling nonpoint source pollution.

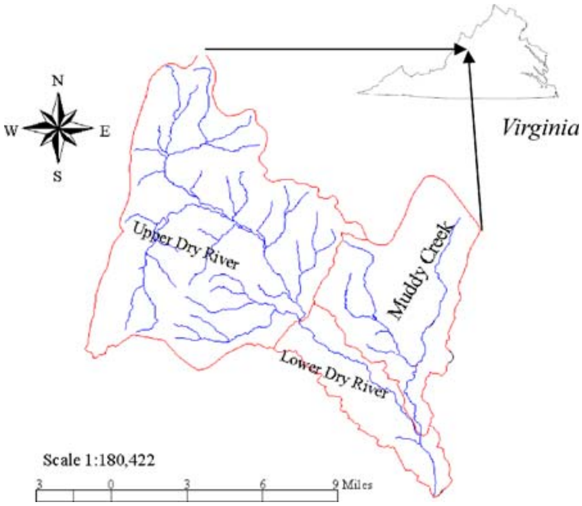

Fig. 2 Location of the Muddy Creek Watershed (Culver et al. 2002)

For example, by 30Q5 with a 1.0-in. uniform storm as the critical condition in a TMDL development, the return period of the joint events is estimated as 30 years (Table 1), which seems more stringent than the continuous simulation. When implementing the integrated control strategy for point and nonpoint sources, the return period of 5 years was required as the design condition for point source, while for NPS control, a 1.0-in. storm (approximately half-year storm) was found to be appropriate for the design storm. This implies that even though an event with a 30-year return period is defined as the critical condition in the TMDL development, which appears quite stringent or conservative, the actual engineering design, however, is based on the 30Q5 for point source control and 1.0-in. storm for NPS control. Both are reasonable design requirements. By controlling both point source and nonpoint source separately in this way, the water quality goal for an impaired water body can be achieved with a small risk factor and at a reasonable cost.

The CFS approach, a design storm-based method in essence, makes NPS management more consistent with the traditional approach to point source management. Instead of allowing the

Table 1 The joint return period of a low stream flow with various sizes of storms

	Stream flow	Size of storm (in.)	Return period	Joint probability	Return period of joint events (year)
1	30Q5	0.6	3-month	1/180	15
2	30Q5	1.0	6-month	1/360	30
3	30Q5	2.5	1-year	1/720	60
4	30Q5	3.0	2-year	1/1,440	120

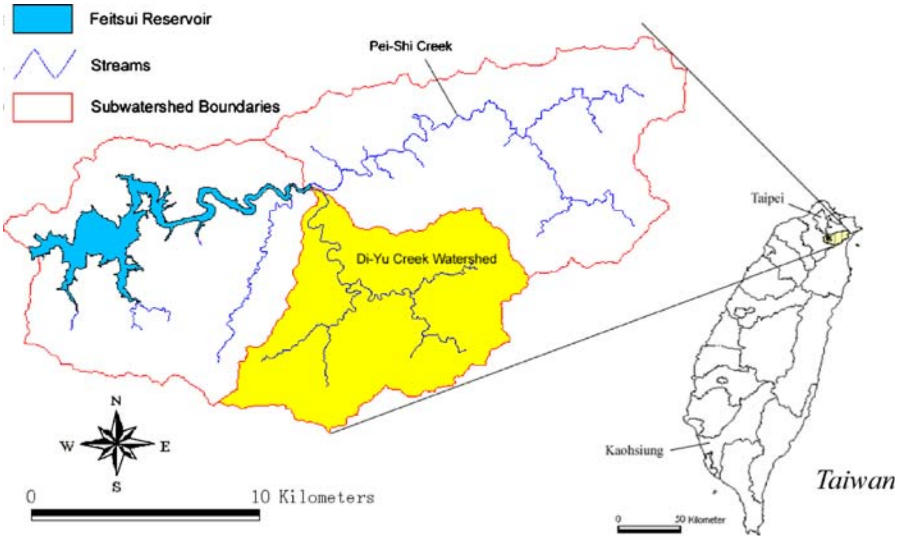

Fig. 3 Feitsui Reservoir Watershed and study area (Lin and Hsieh 2003)

management plan complete dependence on the characteristics of the period selected under the continuous simulation approach, the CFS approach can be used for TMDL development and for assessing the risk associated with a certain load reduction scenario.

The present paper describes the application of the CFS approach in TMDL development for real-world case studies—the Muddy Creek nitrate TMDL study in Virginia and the Dy-yu Creek water quality study in Taiwan.

Background of the study sites

The Muddy Creek watershed is located in Rockingham County in northwestern Virginia (Fig. 2). Muddy Creek generally flows south to its confluence with the Dry River, which joins the North River approximately 3.63 km (2.25 mi) farther to the south. The North River discharges to the South Fork of the Shenandoah River, a tributary of the Potomac River that eventually flows into the Chesapeake Bay.

Virginia's water quality standard for nitrate in the reaches designated for drinking water is 10 mg/L nitrate as nitrogen (9 VAC 25-260-140).[2] Historically, elevated nitrate concentrations have been recorded in Muddy Creek and occasionally for locations close to the Bridgewater Water Treatment Plant (WTP) Intake. Nitrogen is attributed to both point and nonpoint sources in the watershed. The only active and significant permitted point source within the watershed is a poultry processing industry. In general, nonpoint source nitrogen originates from residential, agricultural, and natural sources. Specific nonpoint sources include land application of cattle manure and poultry litter, runoff from concentrated animal operations, grazing livestock, nitrogen-based fertilizer applications to agricultural and residential lands, septic tanks, atmospheric deposition, wildlife waste, and decaying organic matter.

On the other hand, the Dy-yu Creek is a tributary to the Peishi Creek, which flows into the Fei-tsui Reservoir, a major drinking water source for the metropolitan city of Taipei in Northern Taiwan, as shown in Fig. 3. The Dy-yu watershed area is about 78 km^2, with major land use in forest, some tea gardens, agriculture, small villages, and roads. The watershed contributes sediment and nutrient loads into the Fei-tsui Reservoir (Lin et al. 2000; Lin and Lee 2004).

According to the above description, both watersheds are about the same size but differ significantly in their land use, key pollutant, as well as annual rainfall. Those comparisons are detailed in Table 2.

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[2] Criteria For Surface Water, Virginia Water Quality Standards (2007).

Table 2 Comparisons of Dy-yu creek watershed and Muddy creek watershed

	Watershed area (km^2)	Land use	Key pollutant	Annual rainfall (mm)
Muddy Creek, Virginia	80.1	Forest (34.2%) Crop/Farm (30.9%) Pasture (30.0%) Urban (4.8%) Barren (0.1%)	NO_3–N	1,085
Dy-yu Creek, Taiwan	78.54	Forest (95.12%) Tea Garden (2.02%) Others (2.86%)	TP	3,000∼3,600

Methodology

The present study employs the CFS approach and selects the proper NPS model for estimating the concentration of pollutants under selected rainfall depths.

The CFS approach: combinations of low flow conditions and storm patterns

The low flow conditions Q_{75} (a flow exceeded by 75% of the flows annually) or 7Q10 (the lowest flow averaged over a period of seven consecutive days that, statistically, can be expected to occur only once every 10 years) are presumed as the initial conditions of the stream with pollution only from point sources and base currents, and thus associated with a small storm that can flush pollutants from nonpoint sources into the stream when the initial condition of nonpoint sources is relevant to the numbers of previously dry days. One hypothesis is that the initial condition of any storm has to be the same to simulate design hyetographs of different rainfall depths and durations.

On the other hand, design storm is based on the historical data of rainfall in the area. As an example of Dy-yu Creek watershed, the weighted rainfall data are first obtained by applying Thiessen's Polygons Method, which is widely adopted for estimating the area rainfall of watershed in Taiwan. Then, the rainfall intensity (i) can be determined by means of the Horner equation (Wang et al. 1998), as shown in Eq. 1.

$$i = \frac{A}{(t+d)^n} \tag{1}$$

where,

i	average rainfall intensity (mm/h)
t	rainfall duration (min)
A, d, n	constants

The empirical parameters (A, d, n) in Eq. 1 can be obtained by collecting long-term local rainfall data and analyzed by the Log Pearson type III distribution (Wang et al. 1998). Once the rainfall intensities are known, the storm patterns can be developed by the Alternating Block Method (Chow et al. 1988) with suitable durations and recurrence intervals.

The NPS simulation model: BASINS/WinHSPF

Hydrological modeling is important for watershed management as hydrology is the driving force behind many processes occurring on the watershed. In order to explain the mechanisms governing processes in a water body (streams, lakes, or groundwater), hydrology and hydrological relationships must be investigated and simulated. Hydrological models, nowadays, are either an integral part of models simulating water quality in watersheds or are precursors to such models and provide input to them.

Therefore, the present study selects Hydrological Simulation Program—FORTRAN (HSPF), a comprehensive model developed by United States Environmental Protection Agency (USEPA), for simulation of watershed hydrology and water quality for both conventional and toxic organic pollutants such as suspended solid SS, total phosphorus TP, or NO_3–N (Donigian et al. 1995; Laroche et al. 1996). WinHSPF was designed as an interactive Windows interface to HSPF. The

WinHSPF model is used as a component of the USEPA's BASINS (Better Assessment Science Integrating Point and Nonpoint Sources) watershed modeling system. BASINS/WinHSPF is a proven, tested continuous simulation watershed model. It is one of the models recommended by the USEPA for complex TMDL studies.

The BASINS/WinHSPF model uses information such as the time history of rainfall, temperature and solar radiation; land surface characteristics such as land use patterns; and land management practices to simulate the processes that occur in a watershed. The result of this simulation is a time history of the quantity and quality of runoff from an urban or agricultural watershed (Bicknell et al. 1996).

The development steps

Referring to the CFS steps provided by Zhang (2000), after considering recurrence intervals of storm events and then processing model analyses for different design hyetographs, the impacts on water quality can be evaluated accordingly. The main steps in CFS analysis are listed as follows:

1. Determining low flow: flow conditions and previous precipitation are included in the initial conditions of critical storms, which are sensitive to simulation results. If the flow in the initial conditions is assumed as Q_{75} or 7Q10, the extent of water pollution will be limited to the impacts from point sources and base current.
2. Determining storm patterns (as an example of Dy-yu Creek watershed): the design storm is based on the historical data of rainfall in the area, and the rainfall intensities can be determined by empirical equations. Finally, storm patterns can be developed by the Alternating Block Method (Chow et al. 1988) with suitable durations and recurrence intervals.
3. Model simulation: BASINS/WinHSPF model is applied to the simulation of flows, total phosphorus TP, or NO_3–N. With inputs from the aforementioned storm patterns, the concentration variation of the pollutants can be obtained, and the critical conditions, which mean the greatest impacts or highest concentration of pollutants for river water quality, will be determined accordingly. The above methodology has been proven successful in the metropolitan Taipei area (Hsieh 1999) and the critical conditions (defined as the combination of low flow and storm that caused the highest pollutant concentration in the river) could be successfully obtained by the above CFS approach.

Results and discussion

Results of TMDL analysis for Muddy creek watershed, Virginia

The following example is given to further illustrate the CFS concept. Assuming the only available data (Zhang and Yu 2004b) are from September 1993 to December 1995, the most limiting condition was determined for December 6, 1994 by continuous simulation based on this information (nitrate–nitrogen concentration of 12.5 mg/L; Fig. 4). The determination of the critical condition came with the same results as the one using the data from 1993 to 1997 in actual TMDL development. This may be viewed in another way. The model is first calibrated using the data from 1993 to 1995, and then new information regarding 1996 to 1997 was added. The most limiting condition remains unchanged by either using the data set of 1993 to 1995 or 1993 to 1997.

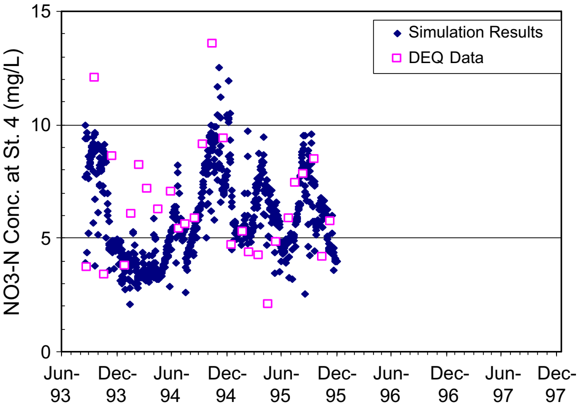


Fig. 4 Model calibration using data from 1993 to 1995 (Zhang and Yu 2004a)

In reality, due to the stochastic nature of storm events and their associated nonpoint source load to the receiving water body, utilizing specific multiple-years as the representative simulation period in continuous simulations may not capture the most limiting condition of a specific water body. For example, the historical storm on May 5, 1996 to May 6, 1996 was 17.8 mm (0.7 in.). However, if a hypothetical storm with total depth of 30.5 mm (1.2 in.) instead of the historical storm of 17.8 mm (0.7 in.) happened on that same day, the updated simulation results would indicate the critical condition previously defined by using the data from 3-year period (1993 to 1995) was no longer valid during the 5-year period (1993–1997). Instead, the storm during May 5, 1996 to May 6, 1996, combining with pre-storm flow condition, would cause the worst water quality violation in the stream. The 30.5-mm (1.2-in.) storm is not rare in the real world (with a return period of approximately 0.5 year for the watershed in this study). Therefore, the above example shows that even when using the representative hydrologic period (even considering a combination of both wet and dry years), there is no guarantee that this selected hydrologic period (i.e., 1993 to 1995) will catch the most limiting condition that might occur at other times (i.e., May 5, 1996–May 6, 1996).

The disadvantage of using continuous simulation in defining critical conditions could be further illustrated in the TMDL allocation process (Moore et al. 1988). Assuming a feasible scenario has been chosen based on the information from 1993 to 1995 through continuous simulation, the water quality goal is met during the historical condition in 1996 and 1997 (Fig. 5). However, if the hypothetical storm (30.5 mm or 1.2-in.) indeed happened, it is evident that the water quality violation would occur during the period of 1996 to 1997 (nitrate concentration of 12.1 mg/L on May 6, 1996, above 10 mg/L water quality criteria; Fig. 6). The observation again indicates that the subjective selection of a representative hydrologic period (i.e., 1993 to 1995 in this case) does not necessarily cover the real critical condition for a receiving water body, which could occur at another time outside the range of the available data (i.e., 1996–1997 in this example). One shortcoming of continuous simulation in defining critical conditions is that allocation scenarios established using current available information might not be sufficient to provide an assurance of meeting water quality goals in the future. In contrast, the CFS explicitly defines the critical condition as a combination of stream flow and storm size, which is especially applicable for a receiving water body impacted by both point and nonpoint sources.

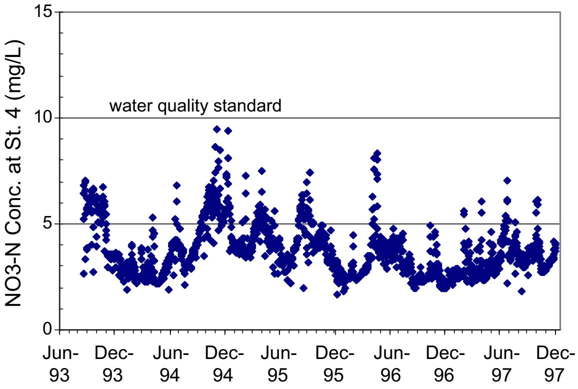


Fig. 5 Allocation using historical storm on May 5 and May 6, 1996 (rain depth = 17.8 mm or 0.7 inch (Zhang and Yu 2004a)

In this section, a comparison has been made between the CFS approach and continuous simulation using the same dynamic watershed and water quality models (e.g., BASINS/WinHSPF). The advantage of using the same model for two different approaches is to minimize the differences in the results due to the modeling tools.

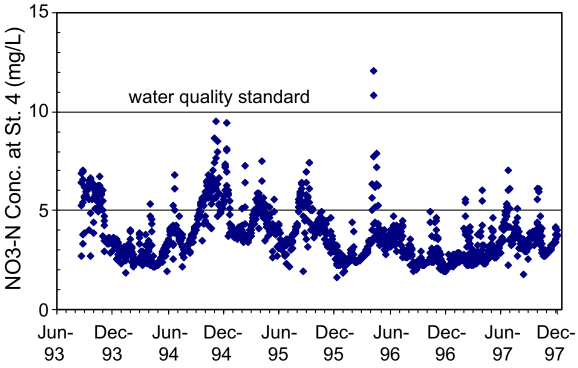
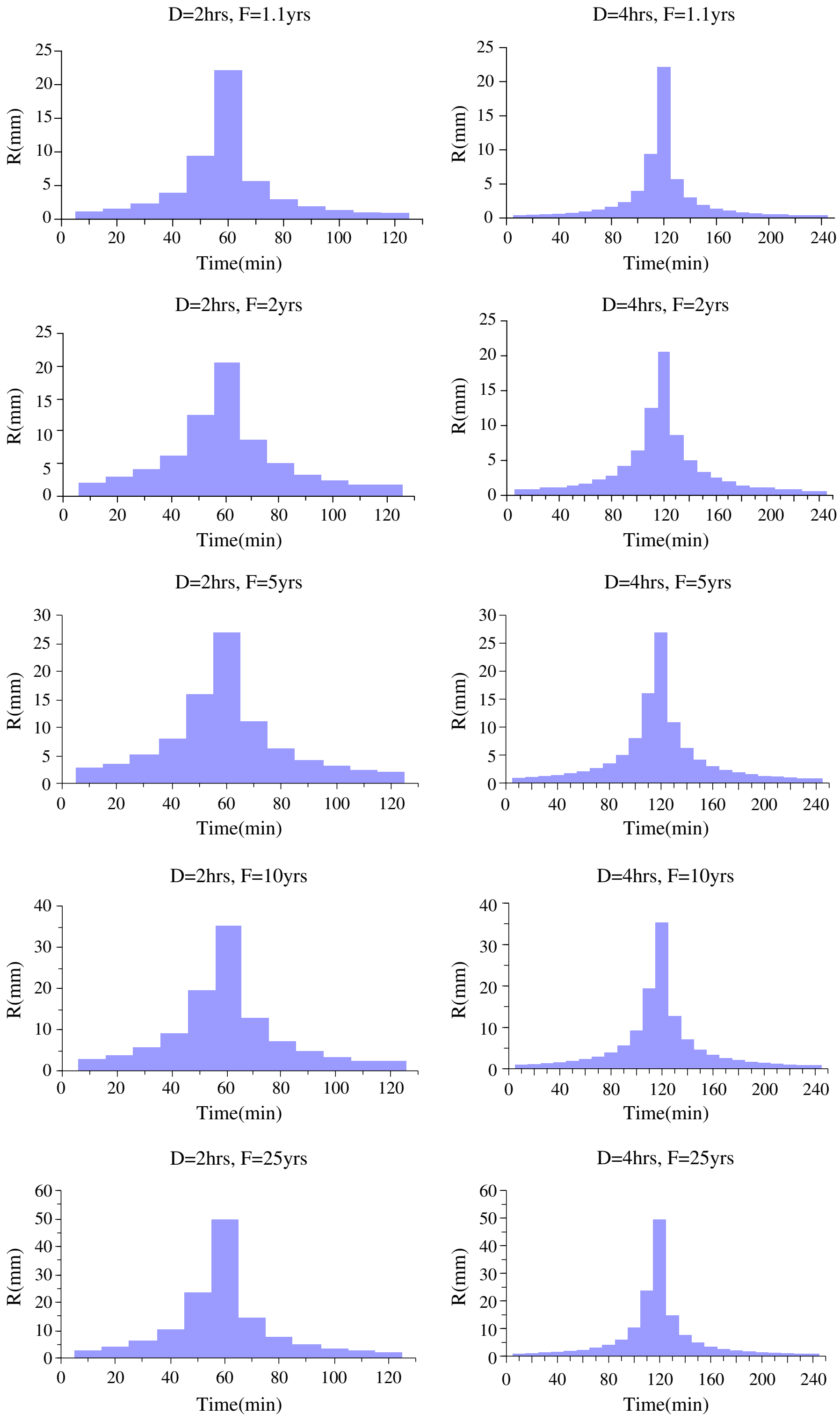


Fig. 6 Change of allocation using hypothetical storm on May 5 and May 6, 1996 (rain depth = 30.5 mm or 1.2 in. (Zhang and Yu 2004a)

Fig. 7 Design storm patterns: rainfall depth vs. time for 2- or 4-h durations (D) and various frequencies (*F*)



Results of Dy-yu creek watershed, Taiwan

The Taiwan results provide some interesting comparisons to those obtained for Muddy Creek in Virginia. Traditionally, the purpose for controlling water quantity is to design based on the storm with high recurrence intervals for flood control. However, for water quality, a smaller storm is physically more important than a larger one. Thus, the study considers ten types of design storms combined with a duration of 2 or 4 h and return periods of 1.1, 2, 5, 10, and 25 years, as the rainfall control factor of critical storms in the Dy-yu creek watershed. The design storm patterns are shown in Fig. 7.

The Storm patterns developed by the Alternating Block Method are such as 2- or 4-h duration with 1.1-year return period (2–1.1, 4–1.1), 2- or 4-h duration with 2-year return period (2–2, 4–2), 2- or 4-h duration with 5-year return period (2–5, 4–5), 2- or 4-h duration with 10-year return period (2–10, 4–10), and 2- or 4-h duration with 25-year return period (2–25, 4–25). The storms are assumed to be evenly distributed in the whole Dy-yu watershed. Besides, the hydrology and water quality parameters of the simulation model, BASINS/WinHSPF, have to be calibrated and validated before simulations of flow and the concentration of the key pollutant, total phosphorus (TP) in the river.

With the initial flow in the river assumed to be Q_{75} and design storms with various return periods and durations superimposed, the modeling simulation generated results for the flow in Dy-yu creek as shown in Fig. 8. It is noted that a hydrographs show a quick rise and fall in flow magnitudes, mostly due to the relatively steep terrain of the watershed.

The results of water quality, total phosphorus TP, simulations are depicted in Fig. 9, in which the critical condition was found to be a 2-h duration, and 1.1-year return period storm, combining with a 75% low flow in the creek. These results clearly echoed those obtained in Virginia in that there does exist a critical condition.

As shown in Fig. 9, the concentration of TP will reach a climax, 0.36 mg/L when combining a 75% low flow and a 2-h duration, and 1.1-year return period storm. Under this circumstance, the utmost concentration of TP is 18 times as much as that stipulated in the local regulation "Surface Water Classification and Water Quality Standards" enacted by Taiwan's EPA where the allowable concentration of TP is less than 0.02 mg/L. Therefore, active measures must be taken to alleviate the deterioration of the water body especially during a small- to medium-sized storm. Furthermore, the dilution of the TP concentration will become prominent as the rainfall intensity increases for both 2- and 4-h duration storms. Figure 9 also shows that the TP concentration of the 4-h duration storms seem to be more fluctuating than those of the 2-h duration storm under the same rainfall intensity. One possible explanation is that the

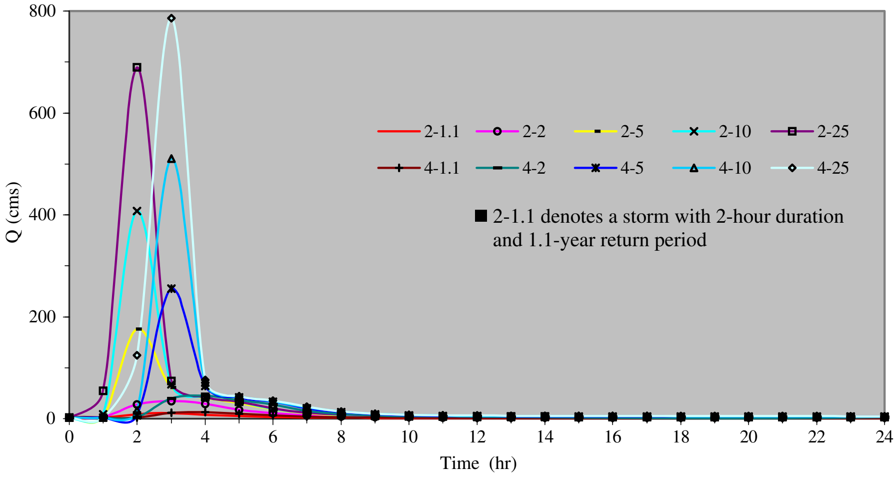
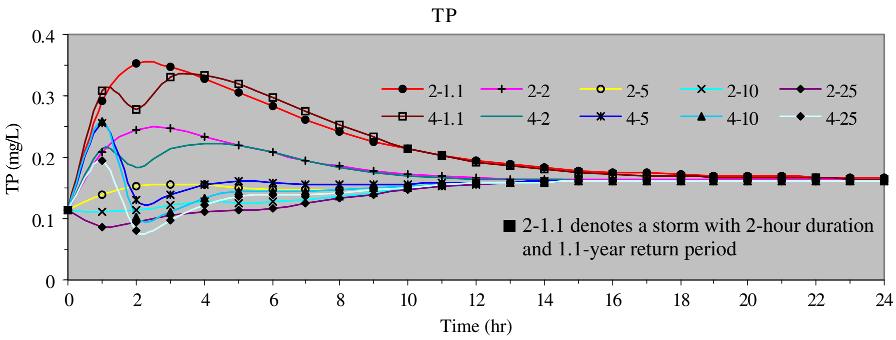


Fig. 8 Simulation result of the flow in Dy-yu creek watershed

Fig. 9 Simulated result of TP for various design storm patterns combing with a 75% low flow



storms with longer duration may not have strong flush, and therefore, their critical conditions are less evident than those of shorter duration.

It can be concluded from case study of the Dy-yu creek that the worst condition really exists by applying the storm event-based CFS approach, and it occurs at a small-sized storm, 2-h duration and 1.1-year return period, and it happens generally at very early stage of the storm event.

Comparisons of critical conditions among different watersheds

In another study on critical storms, Hsieh (1999) applies the VAST and theWASP5 models to examine the water quality of the Keelung River in Northern Taiwan under differently low flow and storm scenarios. Hsieh's results show that both a 2-h duration with 2-year return period storm and a 4-h duration with 5-year return period storm would cause critical conditions in the river. This compares to the study by Zhang (2000) who employed the BASINS/WinHSPF model to simulate the water quality in Muddy Creek Watershed and found that a storm with a duration of 11 h and a rainfall depth of 1.4 in. created the greatest water quality impact.

It is worthy of noting that the target areas in the above study have relevantly smaller watersheds. The small watershed is seen as more sensitive to hydrology and pollutant load augment. Therefore, the critical condition from combined effect relating to initial wash-off and subsequent dilution within a storm event appear more prominent. The above comparisons of critical conditions among different watersheds are summarized as shown in Table 3.

Discussion: impacts of other factors on critical conditions

1. Storm pattern
   Muddy Creek Watershed (Virginia)
   In general, a design storm can be defined by a value for precipitation depth at a point, by

Table 3 Comparisons of critical conditions among different watersheds

Study area	Muddy Creek (Zhang 2000)	Dy-yu Creek (present research)	Keelung River (Hsieh 1999)
Watershed area	80.1 km^2	78.54 km^2	501 km^2
Simulation model	BASINS/WinHSPF	BASINS/WinHSPF	VAST, WASP5, QUAL2E
Key pollutants	NO_3-N	TP	SS, BOD, DO
Low flow	7Q10	Q_{75}	Q_{75}
Storms tested	Duration of 11 h with rainfall depths of 0.1, 0.3, 0.6, 1.0, 1.4, 2.0, 2.5, 3.0 in.	Duration of 2 and 4 h with return periods of 1.1, 2, 5, 10, 25 years	Duration of 2 and 4 h with return periods of 2, 5, 10, 25 years
Critical condition(s)	Low flow (7Q10) + Storm (1.4 in.)	Low flow (Q75) + Storm (2–1.1)[a]	(1) Low flow (Q75) + Storm (2–2)*, (2) Low flow (Q75) + Storm (4–5)*

[a] Storm (a–b) denotes "a"-hour duration combined with "b"-year return period

a design hyetograph specifying the time distribution of precipitation during a storm, or by an isohyetal map specifying the spatial pattern of the precipitation (Chow et al. 1988). Therefore, a design storm can have many types of temporal distribution. As noted earlier, even for storms with the same depth, their impacts on the water quality response could be different if the storm patterns (temporal distributions within the storms) are different.

There are generally four temporal patterns for a storm, namely, uniform, early peak, central-peak, and late-peak, depending on the location of the precipitation peak in the hyetograph (Garen and Burges 1981; US Weather Bureau 1961). For the purpose of flood control, the USDA Natural Resources Conservation Service (NRCS) developed 24-h storm distributions to represent the critical rainfall and runoff volumes for peak discharges. These curves are applicable to the various regions. Types I and IA represent the Pacific maritime climate with wet winters and dry summers. Type III represents Gulf of Mexico and Atlantic coastal areas where tropical storms bring large 24-h rainfall amounts. Type II represents the rest of the country, including the study area of this analysis. The NRCS type II represents the central-peak distribution of a storm. Based on the distribution of NRCS type II, the early peak and late-peak storm patterns were synthesized as shown in Fig. 10. The uniform distribution is also included as a comparison. The total rainfall depth of all four distributions is 35.6 mm (1.4 in.). The simulation results of nitrate concentration in the stream versus the time from the start of the storm are shown in Fig. 11. The hourly peak NO_3–N concentrations and their corresponding daily average concentrations are listed in Table 4.

It can be clearly seen that the storm with uniform distribution caused the worst water quality deterioration of any other temporal distributions. One possible explanation is given as follows. NRCS type II distribution allocates a high percentage of total precipitation in the central part of the hyetograph (above 50%). The combined wash-off and dilution effects for the central portion of the storm (with high rainfall intensity) may offset each other significantly so that the dilution effect could have greater impact. Similarly, the storms with early peak or late-peak distributions allocate a high proportion of total precipitation at the beginning or the end of the storm, respectively. For the uniform storm, however, since the total rainfall depth is evenly distributed over time, the wash-off process could occur gradually but consistently. The dilution effect due to steady augments of the storm runoff may not surpass the effect of the pollutant load increase in the stream. Therefore, uniform storms caused the greatest increase of pollutant concentration in the stream compared

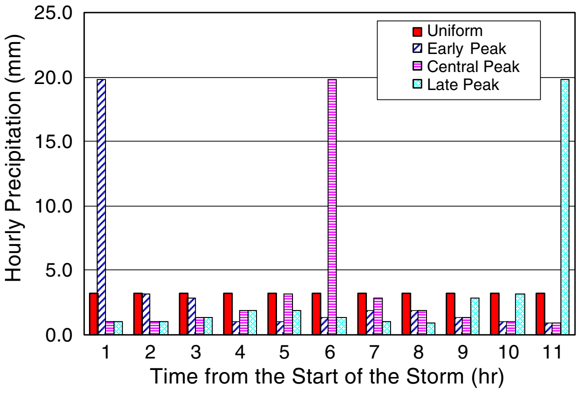


Fig. 10 Hourly precipitation of a 35.6-mm (1.4 in.) storm with four temporal distributions

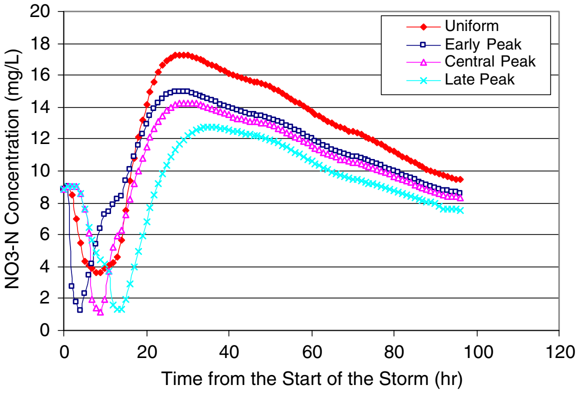


Fig. 11 NO_3–N concentration versus time for a 35.6-mm (1.4 in.) storm with four different temporal distributions

Table 4 Results of in-stream nitrate concentration for a storm with four temporal distributions

Distribution	Uniform	Early peak	Central peak	Late peak
Hourly peak NO_3–N conc. (mg/L)	17.3	15.0	14.3	12.8
Daily average NO_3–N conc. (mg/L)	15.7	13.7	13.2	12.2

with other types of temporal distributions. While more case studies could be done to further verify the above explanations, the main objective of this analysis is to demonstrate the importance of the different temporal distributions of a storm on the receiving water body.

2. Pollutant characteristics
   The critical condition may vary depending upon the type of pollutant and the physical characteristics of the impaired water body in question. The most critical condition for different water quality parameters and even for the same parameter in different receiving water bodies would be different. More example plots are included in Zhang (2000) and Zhen et al. (2004) for total Kjehldahl nitrogen (TKN), biochemical oxygen demand (BOD), and fecal coliform concentrations at various sizes of watersheds versus their corresponding stream flow. While TKN, as one of the nitrogen species, illustrates a similar trend like the scatter plots for nitrate, BOD, and especially fecal coliform do not quite fit the shape of pollutant concentration versus stream flow. Therefore, although the general recommendation for critical conditions in the TMDL development is for a low flow combining with a small storm, care should be taken in dealing with specific pollutants such as coliform bacteria. Fecal coliform has a high die-off rate in the aquatic environment, thus making the effect of dilution less prominent compared to other pollutants (USEPA 1997).
   Besides, based on the TMDL guideline, one TMDL is designed for one specific pollutant in an impaired receiving water body. As discussed earlier, the critical condition may vary depending upon the pollutant characteristics of the impaired water body in question. Therefore, the CFS approach may generate better results for certain pollutants than other types in one particular receiving water body.
3. Limitations of the CFS approach
   The CFS concept is supported and validated by theoretical proof as shown in Zhang (2000). Alternatively, similar to other methods, there are certain limitations of the CFS approach.
   First of all, in the derived conceptual model, it assumes that there is a finite total amount of pollutant loads that could be washed-off from one storm and that the first-flush phenomena holds true. Therefore, the CFS concept should be more applicable for a watershed that is highly impervious, as stated in the development of the conceptual model (Zhang 2000). As land imperviousness decreases, the critical condition defined by the CFS approach may become less distinctive. Furthermore, the sediment detachment process may occur during large storm events. In such cases, there might be a second peak for the pollutant concentration profile, and the critical condition would not be unique.
   The CFS concept and approach has been demonstrated with its applicability under real-world watershed conditions, i.e., Muddy Creek in Virginia and the Dy-yu Creek in Taiwan. In these case studies, although the percentage of imperviousness is relatively low for agricultural land, the sizes of the watersheds are small. Therefore, the water quality response in the stream is still sensitive to the pollutant loads washed off from the land surfaces by storm runoff. For a larger watershed, the CFS concept is generally less evident as shown in some scatter plots of pollutant concentrations versus their corresponding stream flows (Zhang and Yu 2004a).

Conclusions

In this study, a storm event-based CFS approach was developed as an alternative method for determining TMDL for a water body impacted by both point and nonpoint source pollution. This approach is based on the CFS concept; when combining point and nonpoint sources, there appeared to be a critical scenario in which an initial low flow combined with a small storm would cause the worst pollutant concentration levels in the stream. Therefore, the CFS approach is more protective of water quality by reducing the risk of violations since a reasonable limiting condition of receiving water body is covered. The real case studies, Dy-yu Creek Watershed in Taiwan and Muddy Creek Watershed in Virginia, have shown that critical conditions really exist and could be obtained by applying the CFS approach. Comparisons of critical conditions among different watersheds and factors influencing critical conditions were also discussed.

The major benefits of applying CFS approach are such as:

1. The CFS approach offers reasonable results, in which only a limited number of storm events need to be simulated. Therefore, it could be considered as an alternative approach for TMDL development, especially when multiple-year hydrologic and water quality records are not available and continuous simulation is difficult or impossible.
2. In the continuous simulation, the actual risk associated with the selected time period cannot be explicitly defined. In contrast, the CFS approach addresses the critical condition as a combination of a low stream flow and a small-sized storm, both having certain return periods or exceedence probability; that is, the CFS approach could explicitly evaluate the risk and return period associated with the selected allocation scenarios.
3. Based on simulation results using the CFS approach, recommendations for integrated point and nonpoint pollution control strategies can be developed. Synthetic storms can be created to develop management plans with a specified return period, instead of allowing the management plan to be completely dependent on the characteristics of the period selected for continuous modeling. In a word, the CFS approach will make nonpoint source management more consistent with traditional approaches to point source control.

The present research uses the same simulation model for illustrating the CFS concept and comparing critical conditions among watersheds. However, a case study for comparing the use of the different models has not yet been attempted. For future studies, for example, it may be worthwhile to compare the results from a simpler model using the CFS approach with those from a complex model using continuous simulation. It should be emphasized, however, that the CFS concept and approach will not be dependent on the specific model used for the water quality simulation.

In summary, the CFS approach is well suited for defining the critical condition in TMDL computation and should be considered as an alternative approach for TMDL development.

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