Article

Deriving Optimal Analysis Method for Road Surface Runoff with Change in Basin Geometry and Grate Inlet Installation

Junbeom Jo 1, Changjae Kwak 2,*, Jungsso Kim 3 and Sooyoul Kim 4

1 Department of Advanced Industrial Science, Kumamoto University, Kurokami 2-39-1, Chuo-ku, Kumamoto 860-8555, Japan
2 Disaster Information Prevention Research Division, National Disaster Management Institute, 365, Jongga-ro, Jung-gu, Ulsan 44538, Korea
3 Department of Civil Engineering, Bucheon University, 25, Sinheung-ro 56beon-gil, Bucheon-si 14632, Korea
4 Center for Water Cycle Marine Environmental and Disaster Management, Kumamoto University, Kurokami 2-39-1, Chuo-ku, Kumamoto 860-8555, Japan
* Correspondence: water203@korea.kr; Tel.: +82-52-928-8341; Fax: +82-52-928-8309

Abstract: Road surface-runoffs have been analyzed using various approaches, but inaccurate analysis methods lead to overestimation of the drainage capacity, causing unexpected flood damage in low-lying urban areas. Previous studies have highlighted the importance of considering various parameters for accurate road surface-runoff analysis. This study involves road surface-runoff analysis using an enhanced approach considering simplified and modified drainage basin geometries, road surface and gutter flow travel times, and inlet interception efficiency as key parameters under various road conditions. The topographical road conditions were set as follows: Width (6 m), longitudinal slope of road (2–10%), road surface slope (2%), and transverse slope of gutter (2–7%). The results show that using a modified basin considering road slope conditions for estimating actual flow path length and travel time is better for flow analysis than the simplified rectangular basin. Additionally, the runoff analysis should consider the roadside inlet installation conditions, given that the bypass discharge (i.e., rainfall runoff that is not intercepted by upstream inlets) flows downstream and affects the downstream flow characteristics. Based on these results, an optimal road surface-runoff analysis method was developed, which is expected to be useful for road design.

Keywords: spatially varied flow; basin geometry; travel time; inlet efficiency; road surface runoff

1. Introduction

Most stormwater runoff from urban areas passes over the road surface. Then, the runoff is drained through grate inlets on gutters. This occurs due to changes in the urban runoff environment caused by continuous urbanization and industrialization [1–5]. Therefore, integrated urban water management strategies, such as Low Impact Development (LID) in North America and New Zealand, Water Sensitive Urban Design (WSUD) in Australia, and Sponge City in China, have been developed to mitigate the flood risk in urban areas [6–8]. In these strategies, the proper design of urban drainage systems along with various facilities should be considered in combination to control the amount of runoff on the road surface [9]. If the urban stormwater drainage system does not function properly, the bypass discharge flows into adjacent residential areas, causing flood damage [10–12]. Such flood damage primarily occurs in low-lying urban areas where the surface runoff is concentrated, even under the normal rainfall intensity that does not exceed the design discharge capacity [13]. These studies show that continuously adjusting the design criteria based on practical applications for evaluating the road drainage capacity is essential due to the increasingly frequent heavy rainfall events caused by climate change [14–18]. For instance, Jo et al. [19] proposed a rainfall-runoff analysis algorithm that comprehensively considered parameters of flow characteristics, travel time, and road conditions. They
demonstrated the applicability of the spatially varied flow analysis module on the road surface-runoff analysis. Furthermore, they suggested that other parameters, which have not been considered in previous studies, should be discussed to improve the algorithm’s accuracy in analysis. In addition, Jo et al. [19] had the limitation of considering only one road segment for the analysis. Since the actual road surface discharge is not completely intercepted from one grate inlet, runoff analysis for the continuous road segment considering the efficiency of the inlet is necessary.

Dai et al. [20] conducted physical hydraulic experiments with various road slope conditions to estimate the interception efficiency of the grate inlet. They observed that the change of a road slope highly affects the interception capacity of the grate inlet. Moreover, Kim et al. [21] reported that the drainage capacity of a grate inlet, which plays a critical role in road runoff drainage, is mainly affected by road conditions, such as longitudinal and transverse slopes, surface-runoff discharges, and grate inlet geometries. Therefore, there is an urgent need to develop an optimal road surface-runoff analysis method that reflects the various road conditions and the interception capacities of grate inlets.

The use of critical duration of rainfall for calculating rainfall intensity requires a highly practical and theoretically valid method. To estimate the duration and intensity of rainfall events, FHWA [22], AASHTO [23], and Naqvi [24] calculated the critical rainfall duration using an iteration method, assuming the time from the farthest point in the basin to the interception point as the variable. Despite its complexity compared to the analysis applying a constant inflow time, it has the advantage of reflecting the actual phenomena, such as the characteristics of the basin. In particular, the basin geometry of a simple rectangular drainage basin, commonly used in most surface-runoff models, does not appropriately reflect the longitudinal and transverse slopes of the road. Therefore, a limitation is that stormwater surface-runoff flows only in the gutter direction regardless of the slope of the road.

In the present study, a unidimensional surface-runoff analysis was conducted where various parameters were applied to derive the optimal method for the continuous road segments surface-runoff analysis. The optimal analysis method for road surface runoff was derived by comprehensively applying the following additional parameters: Drainage basin, travel time, and intercepted discharge by grate inlets (these parameters were not considered in previous studies). The drainage basin geometry changed from rectangular to rhombic depending on the road slope conditions. In addition, the travel time on the road surface was calculated by applying the concept of morphological change in the drainage basin. Furthermore, we calculated the surface-runoff in the road with continuously installed grate inlets at regular intervals by applying the interception efficiency obtained from hydraulic experiments [21]. This process is expected to improve the analysis efficiency when performing a road surface-runoff simulation by overcoming the limitation of the previous research that ignored the additional parameters. Moreover, the optimal road surface-runoff analysis method could be selected by analyzing the effect of each parameter from the results of the analytical experiment in which the urban road topographical conditions are reflected. The proposed method is expected to be useful for designing road drainage systems and determining the installation interval of the grate inlets.

2. Method

2.1. Flow Analysis Model

In this study, we used the flow analysis model developed by Jo et al. [19]. They suggested a rainfall-runoff analysis algorithm for the road surface, considering uniform and varied flow analysis modules as parameters. In particular, the modified Manning formula in Equation (1) proposed by Izzard and Hicks [25] was used for the uniform road surface-runoff analysis.

\[
Q = \frac{k}{n} S_x 1.67 \tau^{2.67} S_o^{0.5}
\]  
(1)
where $Q$ is the mean flow rate, $n$ is the Manning number, $K$ is the constant ($K = 0.367$), $S_x$ is the transverse slope of the road, $T$ is the flow width, and $S_o$ is the longitudinal slope of the road.

However, a road surface flow has a hydraulic characteristic in which the discharge linearly increases from upstream to downstream, with the road surface-runoff constantly joining into the gutter. The spatially varied flow analysis was used to consider the flow characteristic shown in Equation (2), representing a hydraulic flow calculation model derived from the differential equation of the spatially varied flow.

$$
\frac{dy}{dx} = \frac{S_o - S_f - \frac{2Q}{gA^2} \frac{dQ}{dx} + \frac{Q^2}{gA^2} \frac{dA}{dx}}{1 - \frac{Q^2}{gA^2}}
$$

(2)

where $y$ is the flow depth, $x$ is the distance from the farthest upstream point, $A$ is the cross-sectional area of gutter flow, $Q$ is the flow rate, $g$ is the gravitational acceleration, and $S_f$ is the frictional slope. $S_f$ is calculated using the following equation:

$$
S_f = \frac{n^2Q^2}{A^2R^{4/3}}
$$

(3)

where $R$ is the hydraulic radius. Equation (2) is the first-order ordinary differential equation for the flow depth solved at each location using the fourth-order Runge–Kutta method [24,26].

The unknown flow depth $y$ in Equation (2) can be solved using the step method, which employs the finite difference form. Therefore, an algebraic equation in the finite difference form, such as Equation (4), may be used as the governing equation for the linear drainage flow.

$$
\frac{1}{g}(Q_2V_2 - Q_1V_1) - \frac{1}{2}S_o(A_1 + A_2)dx + \frac{1}{2}(A_1S_{f1} + A_2S_{f2})dx + \frac{1}{2}(A_1 + A_2)(y_2 - y_1) = 0
$$

(4)

where $dx$ is the distance between points 1 and 2, and $V$ is the mean flow velocity at a given point. Therefore, Equation (4) is a nonlinear equation regarding $y_2$, which can be solved by the Newton–Raphson method [27]. The gutter flow depth at each position can be calculated by sequentially solving Equation (4) using the flow depth of the control section as a known value [19,24,28].

2.2. Cross-Sectional Shape

To solve Equation (4), it is necessary to decide the control section and calculate its critical depth, which is performed by applying the concept of specific energy. These parameters are closely associated with the change of the flow depth according to the location of the gutter. However, the critical depth of a section can be calculated by applying the best-suited solution for the given cross-sectional shape. For instance, the critical depth of a uniform triangular cross-sectional shape (Figure 1a) can be accurately determined by applying an analytical solution. However, for composite triangular cross-sectional shapes (Figure 1b), the critical depth should be calculated using a numerical solution [29]. Many studies report explicit solutions that can be used to obtain the critical depth for complex cross-sectional shapes [30–32]. Figure 1b schematically illustrates the cross-section geometry of the analytical experiment used in the present study. The curbstones slope $S_k$ is perpendicular to the surface, the transverse slope of the road ($S_x$) is fixed at 2%, and the transverse slope of the gutter $S_g$ varies within the 2–7% range. Compared to a circular, trapezoidal, or horseshoe-shaped section, a composite triangle gutter section (Figure 1b) requires further studies on explicit analysis methods for the critical depth. Therefore, in the present study, the critical depth of the composite triangle gutter section was calculated using the numerical solution based on the Newton–Raphson equation. Moreover, a spatially varied flow-based surface-runoff analysis was performed.
2.3. Drainage Basin Estimation Method

In most urban rainfall-runoff models, a runoff analysis is performed by assuming a simple rectangular basin, as shown in Figure 2. Such rectangular drainage basins do not appropriately consider the flow characteristics in the diagonal direction along the longitudinal and transverse slopes of the road. Moreover, it underestimates the road surface flow-travel time because the distance from the farthest point of the basin to the upstream end of the gutter, which is similar to the road width, is used.

To calculate the riverine watershed, a different approach is used. One such approach is the SWMM model [33]. It uses the flow path and flow path length according to the slope conditions. Liu et al. [34] and Luo et al. [35,36] determined the flow direction by considering the road slope conditions when calculating the road surface flow (Figure 3). However, there is no established method for the road surface-runoff analysis considering the change of the basin geometry due to a lack of sufficient discussion. Herein, the road surface-runoff discharge was estimated by applying the flow path length considering the road slope conditions used in riverine drainage basin calculations.
Figure 3. Schematic of the road surface flow calculation ($B$: Road width, $\gamma$: Angle of the flow path, $\ell$: Flow path length, $\theta$: Flow slope, $\alpha$: Longitudinal slope of the road, and $\beta$: Transverse slope of the road).

In Figure 3, $L$ is the road length between the upstream and downstream grate inlets, $B$ is the road width, $\ell$ is the flow path length considering the road slope conditions, $\alpha$ is the longitudinal slope of the road, $\beta$ is the transverse slope of the road, $\gamma$ is the angle of the flow path, and $\theta$ is the flow slope. The angle of the flow path, flow slope, and flow path length are given by Equations (5)–(7), respectively.

$$\gamma = \tan^{-1}(\tan \beta / \tan \alpha) \quad (5)$$

$$\theta = \tan^{-1} \sqrt{(\tan \alpha)^2 + (\tan \beta)^2} \quad (6)$$

$$\ell = B / \sin \gamma \quad (7)$$

For the road surface-runoff analysis, the experimental conditions for roads were set to the values listed in Table 1 based on the road design criteria [22,23,37,38] and a previous study [21]. The experimental conditions for the drainage basin were selected as listed in Table 2 by applying the slope-dependent travel length, which was calculated using the road width and the longitudinal and transverse slopes of the road with Equations (5) and (7), respectively.

Table 1. Experimental conditions for roads.

<table>
<thead>
<tr>
<th>Condition</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Road width $B$ (m)</td>
<td>6 (two lanes)</td>
</tr>
<tr>
<td>Road length $L$ (m)</td>
<td>20, 100, 200</td>
</tr>
<tr>
<td>Longitudinal slope of road $\alpha$ (%)</td>
<td>2, 4, 7, 10</td>
</tr>
<tr>
<td>Transverse slope of road $\beta$ (%)</td>
<td>2</td>
</tr>
<tr>
<td>Transverse slope of gutter $S_g$ (%)</td>
<td>2, 4, 7</td>
</tr>
</tbody>
</table>

Table 2. Experimental conditions for drainage basins.

<table>
<thead>
<tr>
<th>$\alpha$ (%)</th>
<th>$\beta$ (%)</th>
<th>$B$ (m)</th>
<th>$\ell$ (m)</th>
<th>$\gamma$ (°)</th>
<th>$\ell$ (m)</th>
<th>$\gamma$ (°)</th>
<th>$A$ (m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>4</td>
<td>6</td>
<td>8.49</td>
<td>45</td>
<td>13.43</td>
<td>26.56</td>
<td>120</td>
</tr>
<tr>
<td>7</td>
<td>2</td>
<td>6</td>
<td>21.93</td>
<td>15.92</td>
<td>30.88</td>
<td>11.27</td>
<td></td>
</tr>
</tbody>
</table>

Under the condition of the simplified rectangular basin, surface rainwater runoff forms a flow path perpendicular to the gutter, and the surface flow path length is the same as the road width (6 m) regardless of the slope condition at 90° to the gutter flow (Figure 3).
Under the condition of the simplified rectangular basin, surface rainwater runoff forms a flow path perpendicular to the gutter, and the surface flow path length is the same as the road width (6 m) regardless of the slope condition at 90° to the gutter flow (Figure 4a). On the contrary, in the modified basin, considering the slope distance, the higher the longitudinal slope of the road, the smaller the angle of the flow path, with the flow path length increasing along the flow path. The changes in the drainage basin considering this feature are shown in Figure 4b,c.

Even in the modified basin that considers the road slope condition, if the width and length of the road are identical, the surface area of the road that intercepts rainwater is also constant as that of the simplified drainage basin. However, the travel time of the surface flow increases as the flow path length is extended. This condition becomes a substantial variable in determining the design rainfall intensity based on the actual travel time.

Figure 4. Changes in patterns of surface-runoff in a drainage basin considering the slope conditions of the road: (a) Simplified drainage basin ($l = 6$ m, $\gamma = 90^\circ$), (b) modified basin ($l$: 8.49 m, $\gamma$: 45°) under the 2% longitudinal and 2% transverse slopes, (c) modified basin ($l$: 13.43 m, $\gamma$: 26.56°) under the 4% longitudinal and 2% transverse slopes.
2.4. Travel Time Estimation Method

The flow–travel time is a key factor in selecting the maximum rainfall design by applying it as the rainfall duration when determining the rainfall intensity. FHWA [22] defines the total travel time as the sum of the travel time of the surface flow from the farthest point of the basin to the upstream end of the gutter (travel time of surface flow \((-\rightarrow)\) in Figure 4) and the travel time of the gutter flow from the upstream end of the gutter to the downstream end of the gutter (travel time of gutter flow \((-\rightarrow)\) in Figure 4). The road surface and gutter flows are calculated using different equations, and the total travel time is defined by Equation (8).

$$T_f = T_s + T_g$$  \hspace{1cm} (8)

where $T_f$ is the total travel time, $T_s$ is the travel time of the surface flow, and $T_g$ is the travel time of the gutter flow.

Several empirical equations, such as the SCS and Kerby (overland flow and transitional channel flow), have been developed and suggested to calculate the road surface travel time. In this study, the Kerby equation for the overland flow was used, as shown in Equation (9).

$$T_s = 1.445 \left( n \times \frac{l}{S} \right)^{0.467}$$  \hspace{1cm} (9)

where $l$ is the flow path length and $S$ is the flow slope. For a simplified basin model, the road width $B$ is applied as the flow path length $l$, and the longitudinal slope of the road $S_o$ is applied as the flow slope $S$. The flow path length $\ell$ expressed in Equation (7), and the flow slope $\theta$ given in Equation (6) were applied for a modified basin model.

Different methods were used to calculate the travel time in the gutter, depending on the analysis model. In the case of the spatially varied flow model, as flow characteristics vary depending on the location of the gutter, the gutter travel time was obtained by adding all values in Equation (11) after calculating the travel time in the gutter between sequentially estimated measurement points in each segment (Equation (10)).

$$t_i = \frac{dx}{v_i}$$  \hspace{1cm} (10)

$$T_g = \Sigma t_i$$  \hspace{1cm} (11)

where $t_i$ is the travel time in the gutter, $dx$ is the distance, and $v_i$ is the mean flow velocity between the measurement points of each segment.

In recent years, various studies have considered applying the critical duration used to determine the rainfall intensity duration as a reasonable travel time in the rainfall-runoff analysis. In this study, both traditional simplified and modified basins were considered for the runoff analysis. The values of the total road surface discharges calculated from both basins were compared to analyze the effect of the prolonged flow path length on the travel time.

2.5. Grate Inlet Installation Method

Existing analysis methods were derived based on results of a road segment with a single grate on an entire road, assuming that the total runoff is completely intercepted by the subsequent grate inlet or by simply implementing the discharge interception efficiency of an inlet in proportion to the calculated flow depth. These analysis methods do not consider the discharge interception efficiency of inlets depending on inlet sizes and road conditions. Therefore, it is essential to conduct a more detailed analysis to understand the actual road surface-runoff that considers the effect of the grate inlet installation on the road section with the continuously installed inlets. This should be performed so that both the discharge intercepted by the inlets and the bypass discharge flows to the next segment. The discharge interception efficiency with respect to the inlet size and road conditions has been continuously studied based on hydraulic experiments and numerical simulations. In this study, the runoff analysis was performed in a road section where
grate inlets were installed at regular intervals, thereby employing the intercepted discharge estimation formula developed through hydraulic experiments by Kim et al. [21].

Kim et al. [21] proposed an improved equation for estimating the discharge intercepted at a grate inlet under all road slope conditions considered in this study (Table 1) by performing hydraulic experiments. Three different sizes of grate inlets (40 × 50 cm, 40 × 100 cm, and 40 × 150 cm) were used, commonly taken in South Korea and other Asian countries. The estimation equation for the discharge intercepted by a grate inlet considering the road slope condition is given by Equation (12).

\[
Q_i = K' Q_m S_g S_O^{k_1} S_G^{k_2} S_O^{k_3}
\]  

(12)

where \(Q_i\) is the intercepted discharge, \(Q_m\) is the total road surface-runoff, \(S_g\) is the transverse slope of gutter, \(S_O\) is the longitudinal slopes of road, and \(K', k_1, k_2,\) and \(k_3\) are coefficients, whose values for each inlet size are listed in Table 3.

Table 3. Empirical coefficients used in Equation (12) by Kim et al. [21].

<table>
<thead>
<tr>
<th>Inlet Size (cm)</th>
<th>(K')</th>
<th>(k_1)</th>
<th>(k_2)</th>
<th>(k_3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>40 × 50</td>
<td>3.243</td>
<td>0.892</td>
<td>0.317</td>
<td>0.059</td>
</tr>
<tr>
<td>40 × 100</td>
<td>2.525</td>
<td>0.939</td>
<td>0.244</td>
<td>0.058</td>
</tr>
<tr>
<td>40 × 150</td>
<td>1.748</td>
<td>0.952</td>
<td>0.159</td>
<td>0.012</td>
</tr>
</tbody>
</table>

In Section 3.2, after installing a grate inlet (40 × 50 cm) at each end of a gutter segment, the road surface-runoff analysis was performed with continuously installed grate inlets applied to the intercepted discharge under the road slope conditions expressed in Equation (12). The change in the road surface flow depth in a straight road section with a length of 200 m was continuously simulated. The installation intervals were varied between 20 and 40 m to compare the change in the road surface flow depth due to the inlet installation interval. The installation interval was selected based on literature and field surveys. In many countries, it is recommended that the appropriate inlet installation interval be calculated according to the road conditions; in cases where this is difficult to determine, an interval of 20 m is suggested [22,23,37,38]. Moreover, 40 m of inlet installation interval was determined considering the field survey data on the inlet installation status of the Dorimcheon basin in Seoul, Korea.

3. Results and Discussion

In this study, a unidimensional surface-runoff analysis using various parameters not yet considered was conducted to derive an optimal road surface-runoff analysis method. Results are assessed and discussed in this section. In Section 3.1, the analytical experiments were performed after selecting four experimental conditions with the different combinations of the drainage basin and travel time estimation methods. In this phase, the change of the travel time at each condition was investigated, and the total road surface discharge was estimated by applying the calculated travel time as the rainfall intensity duration. Moreover, in Section 3.2, runoff analysis was performed with the continuously installed grate inlets by applying Equation (12) for calculating the discharge intercepted by the grate inlets based on the road conditions. Provided that the bypass discharge is in the gutter until the next grate inlet, the two experimental conditions for the inlet installation spacing (i.e., 20 and 40 m along the gutter) were selected, and the depth change of the gutter flow was calculated at each segment.
3.1. Flow Characteristics Depending on Drainage Basin Geometry Estimation Methods

The simplified rectangular basin artificially represents the flow path and the flow path length of the rainwater runoff based on the road slope conditions. It leads to an inaccurate runoff calculation due to the failure to reflect the actual travel time as the rainfall intensity duration. In this study, the modified basin considering the slope, flow path, and flow path length was applied for the flow analysis. In addition, the road surface- and gutter-travel times were separately calculated to estimate the travel time in more detail. By composing two travel time conditions, four experiments were designed, as listed in Table 4. Each experiment was applied to a straight road segment with a length of approximately 100 m for the spatially varied flow analysis. First, the travel time was calculated to use it as the rainfall duration. Then, the total road surface discharge was estimated using it. Third, the flow characteristics were investigated using the drainage basin estimation method. The calculated travel time and the total road surface discharge were used as primary data for the surface-runoff analysis of the road with the grate inlet continuously installed at regular intervals in Section 3.2.

Table 4. Experimental conditions for the road surface-runoff analysis.

<table>
<thead>
<tr>
<th>Drainage Basin Estimation Method</th>
<th>Travel Time Estimation Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>Simplified rectangular basin</td>
</tr>
<tr>
<td>Case 2</td>
<td>Simplified rectangular basin</td>
</tr>
<tr>
<td>Case 3</td>
<td>Modified basin considering slope conditions</td>
</tr>
<tr>
<td>Case 4</td>
<td>Modified basin considering slope conditions</td>
</tr>
</tbody>
</table>

3.1.1. Analysis of Travel Time

Figure 5 shows the travel time calculated in each experimental condition, in which the longitudinal slope of the road and the transverse slope of the gutter varied. The road surface travel time is determined by the flow path length, which spans from the farthest point of the basin to the upstream end of the gutter. Therefore, the road surface travel time was estimated to be 1.20 min in the simplified rectangular basin in Case 1, which considered the same flow path length as the road width (i.e., 6 m) and neglected the road slope conditions. The road surface travel time at the modified basin in Case 3 was estimated to be 1.30 min on the 2% longitudinal slope of the road and 1.76 min on the 10% longitudinal slope. It demonstrates that the calculated road surface travel time increases as the longitudinal slope increases. It is caused by the variation of the flow path length in the modified basin resulting from the longitudinal slope of the road. In the case of the transverse slope of the gutter, there was no significant change in the road surface travel time since it did not influence the road surface flow. Since the gutter flow velocity determines the gutter travel time, the experiment results can be summarized as follows: The greater the longitudinal slope of the road and the transverse slope of the gutter, the higher the gutter flow velocity and shorter the gutter travel time. In particular, it was found that the increase in the transverse slope of the gutter led to the accumulation of an increased surface flow into the gutter, reducing the gutter travel time due to the increased flow rate and velocity in the gutter.
3.1.2. Analysis of Road Surface Discharges

The total road surface discharge was calculated by reflecting the travel time calculated in Section 3.1.1 for the rainfall intensity duration (Figure 6). By analyzing the effect of each experimental condition on the road surface discharge, we found that Cases 2 and 4, which consider both the road surface and gutter travel time, yielded a longer critical duration that leads to lower rainfall intensity in comparison to the results of Cases 1 and 3, which consider only the road surface travel time. As a result, the total road surface discharge decreased when considering the sum of both the travel times and the rainfall intensity duration. In addition, in Case 1, which considered only the simplified drainage basin and road surface travel time, the total road surface discharge hardly changed in all conditions of the longitudinal slope of the road since the road slope conditions are not appropriately reflected. Therefore, a surface flow analysis should be performed using a modified basin that can reflect the practical topographical conditions of the road. Consequently, a method similar to Case 4, in which
the road surface travel time of the modified basin and gutter travel time were separately calculated and applied as critical duration, is considered best suited for realistic runoff analysis reflecting the longitudinal and transverse slopes of the road.

Consequently, a method similar to Case 4, in which the road surface travel time of the modified basin and gutter travel time were separately calculated and applied as critical duration, is considered best suited for realistic runoff analysis reflecting the longitudinal and transverse slopes of the road.

Figure 6. Road surface discharges due to different transverse slopes of the gutter.

3.2. Road Surface-Runoff Analysis with Grate Inlets Installed at Regular Intervals

Figure 7 shows the changes in the road surface flow depth on a 200 m straight road with grate inlets installed at intervals of 20 and 40 m in Figure 7a,b, respectively. A certain depth of rainwater had already flowed into the upstream gutter, starting from the second segment where the bypass discharge passed through the first grate inlet. This phenomenon repeats whenever the gutter flow passes through the grate inlet, resulting in a higher flow depth in the downstream segments of the road compared to the end of the first segment, where a single segment analysis method is used. In addition, it was verified that the higher the inlet installation interval, the higher the rate of increase in the road surface flow depth. Consequently, when the transverse slope of the gutter was 2%, the depth increased by 25.49% for the installation interval of 20 m, as shown in Figure 7a, and by 30.38% for that of 40 m, as shown in Figure 7b. Furthermore, for transverse slopes of 4% and 7%, the depths increased by 11.84% and 15.27% and by 5.94% and 6.51% for the installation intervals of 20 m and 40 m, as shown in Figure 7a,b, respectively. It shows that the inlet installation interval on road surface-runoff analysis is more significant because the inlet interception efficiency is affected by surface flow characteristics (e.g., total discharge, flow velocity, and flow width). Therefore, an appropriate inlet installation interval, considering the discharge interception efficiency of the inlet in tandem with surface-runoff analysis of a road with continuously installed grate inlets, is essential for an adequate evaluation of the drainage capacity.
Figure 7. Changes in road surface flow depths considering the grate inlet installation interval and intercepted discharge: (a) Inlet installation interval of 20 m and (b) inlet installation interval of 40 m.

3.3. Deriving the Optimal Method for Road Surface-Runoff Analysis

In this study, the optimal method for the road surface-runoff analysis was examined for the unidimensional flow analysis of the road with continuously installed grate inlets. First, the topographical conditions and the size of the grate inlet to be installed were determined. The installation interval $L_i$ of the grate inlet was assumed in the flow analysis. Then, we divided the road length into segments $XL$, with the inlet positions as the reference points. The analysis was conducted in the following order starting from the upstream end ($XL = 1$) (Figure 8).
4. Conclusions

An optimal method for a road surface-runoff analysis considering various road conditions was derived here to evaluate the drainage capacity of the road accurately. Other conditions considered include the road width (6 m) and slope (longitudinal slope of road: 2 to 10%, transverse slope of road slope: 2%, and transverse slope of gutter: 2 to 7%). The analytical experiment used key parameters of the spatially varied flow module, basin geometry (simplified basin/modified basin), travel time (road surface flow/gutter flow), and interception efficiency of the grate inlet. To examine the experimental results, first, the spatially varied flow analysis was performed over the selected four experimental conditions. Then, the optimal method for the road surface-runoff analysis was presented after analyzing the road flows with the continuously installed grate inlets. The dominant conclusions of the study are as follows:
The geomorphology of the road drainage basin changes when considering the different slope conditions of the road. The higher the slope of the road, the longer the flow path length $\ell$. The effect of the longer flow path length is more significant than the higher flow velocity, resulting in a longer surface travel time. Under the longitudinal slope of the road (10%), the surface travel time of the modified basin increased by 46.67% (1.76 min), which is 0.56 min longer than that of the simplified rectangular drainage basin (1.20 min). The road surface discharge is also changed according to the surface travel time. In the optimal method (Case 4), it decreases by 45.58% at 2% and 37.98% at 10% longitudinal slope of the road compared to the simple analysis method (Case 1). Therefore, it is crucial to select a modified drainage basin that reflects both the longitudinal and transverse slopes of the road.

The runoff analysis was performed on the 200 m straight road where the grate inlets were installed at regular intervals in the spacing conditions of 20 and 40 m, respectively. The bypass discharge, which was not intercepted at each road segment, headed downstream along the gutter, and had a continuous effect. In addition, provided the significant effect of the slope condition and road surface discharge on the interception efficiency of the grate inlet, it is essential to perform the runoff analysis at each segment of the road section where the grate inlets were installed at constant intervals.

In this study, the optimal analysis method for the road surface-runoff was developed for a straight road section with continuously installed grate inlets by performing an analytical experiment applying various parameters. The proposed method should be implemented on real roads to verify its implementation for designing a grate inlet on real roads. Furthermore, further research should validate it in complex road conditions of intersections and curved sections, for instance.

Author Contributions: Conceptualization, J.J.; methodology, J.J.; validation, S.K.; formal analysis, J.J.; investigation, C.K.; resources, J.K.; data curation, S.K.; writing—original draft preparation, J.J.; writing—review and editing, J.K. and S.K.; visualization, C.K.; supervision, C.K.; project administration, J.K.; funding acquisition, J.K. All authors have read and agreed to the published version of the manuscript.

Funding: This work is supported by the Korea Agency for Infrastructure Technology Advancement (KAIA) grant funded by the Ministry of Land, Infrastructure and Transport (Grant 22CTAP-C163761-02).

Institutional Review Board Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References


12. Kim, J.S.; Jo, J.B.; Yoon, S.E. Head loss reduction in surcharged four-way junction manholes. Water 2018, 10, 1741. [CrossRef]


15. Li, X.; Fang, X.; Chen, G.; Gong, Y.; Wang, J.; Li, J. Evaluating curb inlet efficiency for urban drainage and road bioretention facilities. Water 2019, 11, 851. [CrossRef]


34. Luo, W.; Wang, K.C.P.; Li, L. Coupled two-dimensional surface flow and three-dimensional subsurface flow modeling for drainage of permeable road pavement. J. Hydrol. Eng. 2016, 21, 04016051. [CrossRef]

35. Luo, W.; Wang, K.C.P.; Li, L. Hydroplaning on sloping pavements based on inertial measurement unit (IMU) and 1-mm 3D laser imaging data. Period. Polytech. Transp. Eng. 2016, 44, 42–49. [CrossRef]
