

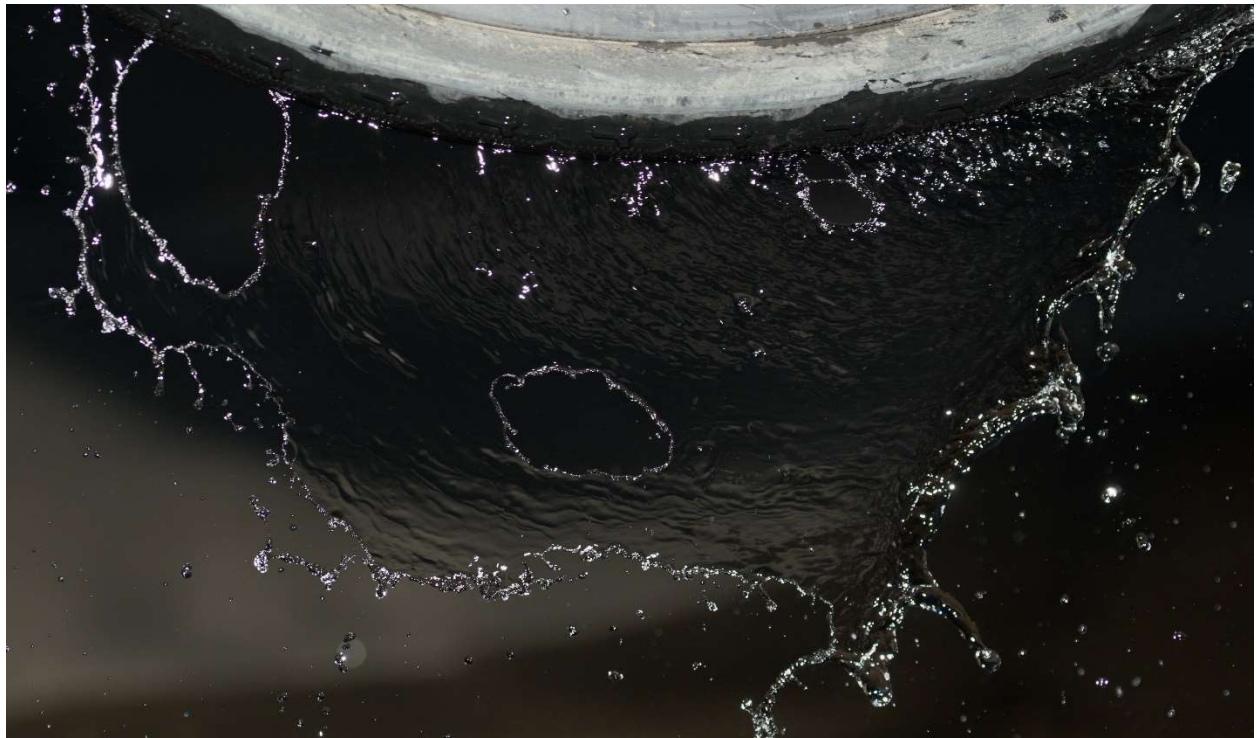
Team First – Falling Water Sheet

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10/05/2026

MCEN 5151: Flow Visualization



Abstract:

In the image shown on the title page, a sheet of water falls from a bicycle tire as it spins. The sheet's surface shows a wavy texture, with holes appearing within as the sheet "tears" into smaller streams and droplets. The image was captured for the Team First assignment in MCEN 5151: Flow Visualization at CU Boulder. All three members of the group (see title page) contributed to setup and visualization of the flow. The intent behind the image was to discover what flow phenomena occur when one rides a bike through a wet surface, and how the spray of water coming from a bike wheel is formed.

To capture the image, a gravel bike with semi-slick tires was mounted on a bike stand to allow the rear wheel to spin freely. Once the wheel was spun up, a hose deposited water onto the tire from just below the bottom bracket. To "freeze" the motion of the water in the image, an external flash was used to illuminate a very brief moment in time. The exposure of the camera was set to keep the rest of the scene dark, and only fully expose what was hit directly by the flash. The image was captured using a Nikon D7500 DSLR, 70-200mm telephoto lens, and GODOX VING V860IIN external flash kit.

Flow Apparatus and Characteristics:

To create the image, the setup shown below in Figure 1 was used.

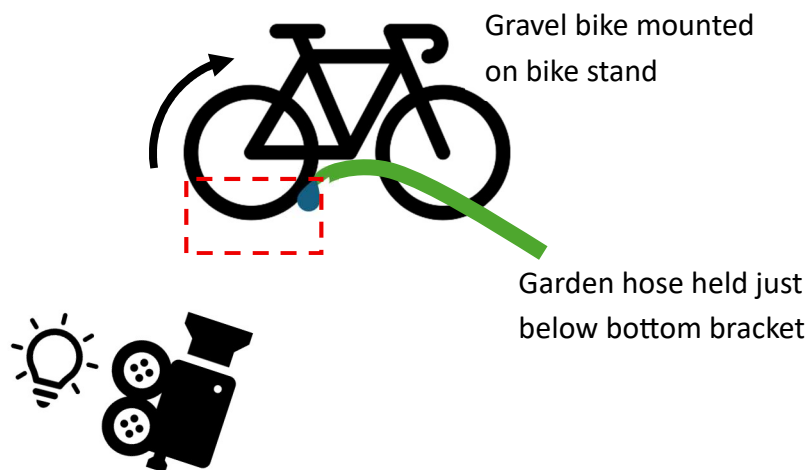


Figure 1: Schematic of the setup used to capture the image. The bike wheel was about 1.5m from the camera's sensor plane, and the wheel was spun at approximately 145 rpm. The red dashed box shows the area photographed.

A gravel bike was mounted on a bike stand, allowing for the rear wheel to be spun freely using the pedals. One team member pedaled the wheel up to speed, then held a garden hose

near the tire to transfer water onto it. A telephoto lens was used to keep away from the water spray while still being able to image fine details in the flow. When taking the picture, the use of an external flash meant that the flow was “frozen” in time, only exposing the camera sensor for an extremely short time while the flash was active.

In the resulting image, a thin sheet of water is seen falling from the spinning bike wheel, with a few holes appearing within the sheet. The sheet’s surface shows curved ripples, illustrating how the water is pulled along with the wheel as it spins. Towards the edges of the sheet, the water can be seen collapsing into individual streams and droplets.

This flow can be approximated as a thin film flow which eventually breaks apart and forms droplets. To analyze the flow, the Weber number (We) can be used. The Weber number describes the relationship between the inertial forces and surface tension forces in a flow [1], and is defined as

$$We = \frac{U^2 \rho l}{\sigma} \quad \text{Eqn. 1}$$

Where U is the velocity of the flow, ρ is the fluid density, l is the characteristic length of the flow, and σ is the surface tension. For this flow, the velocity of the sheet was assumed to be the same as the tangential velocity at the edge of the tire, the water was assumed to be at 50°F, and the characteristic length of the flow was assumed to be to the thickness of the sheet. The values used to calculate the Weber number are shown below in Table 1.

Table 1: Weber number constants

Constant	Value
U	5.3 m/s
ρ	999.7 kg/m ³
l	0.005 m
σ	7.42*10 ⁻² N/m

To determine the tangential speed of the wheel, a slow-motion video was taken with a phone recording at 240 fps, then the number of frames in a single revolution were counted. This process is illustrated below in equation 2:

$$\left(\frac{1 \text{ revolution}}{99 \text{ frames}}\right) * \left(\frac{240 \text{ frames}}{1 \text{ sec}}\right) * \left(\frac{60 \text{ sec}}{\text{min}}\right) = 145.5 \text{ rpm} \quad \text{Eqn. 2}$$

Once the rotation rate was known, the tangential speed was calculated using $V_r = r\omega$ where r is the radius of the wheel and ω is the rotation rate in rad/s. The bike wheel used was 622 mm in diameter and the tire used was approximately 40 mm wide, giving a total diameter of 702 mm. Using this, the tangential speed at the edge of the tire was found to be 5.3 m/s. The thickness of the sheet was estimated by comparing the spray to the tire’s thickness. The density

and surface tension were retrieved from [2] and [3], respectively. Plugging these numbers into Equation 1, the Weber number can be found:

$$We = \frac{U^2 \rho l}{\sigma} = \frac{\left(5.3 \frac{m}{s}\right)^2 (999.7 \frac{kg}{m^3})(0.005 m)}{7.42 * 10^{-2} \frac{N}{m}} = 1892.3$$

To put this Weber number into perspective, it was compared to work done by Binnie [4]. In that work, sheets of water were created by cutting thin slits in the sides of metal tubes, then allowing water to flow through the slit. The Weber numbers were calculated for these sheets and the height at which the sheets began to break-up into droplets was recorded, among other things. Comparing this Weber number to those reported in Table 1 of [4], it is seen that the Weber number of the water stream from the bike tire is much larger than those of the experiments conducted in [4]. Even accounting for the different form of We reported there, the largest Weber number of those streams is equal to 95.2. However, this makes sense when considering the break-up lengths of the streams and their stability. The break-up lengths of the sheets in [4] were on the order of 40-50 inches. In comparison, the sheet coming off the bike broke into droplets after just 4-6 inches. The larger value of We indicates a less stable sheet that is more prone to break into droplets, caused by the high velocity at the tire's edge.

Visualization Technique:

The flow was visualized using a marked boundary technique. By using a flash to illuminate the sheet of water and tire, only they were illuminated. This left sharp, distinguishable boundaries between the tire, water, and air. The bike was placed in front of an open area to minimize reflections and objects the light could bounce back off of, reducing the number of distractions in the image and keeping the background dark.

Imaging Technique:

The DSLR camera, lens, and exposure specifications are shown in the table below.

Table 2: Camera and image specifications

Camera model	Nikon D7500
Lens model	AF-S NIKKOR 70-200mm 1:2.8G ED VR II
Focal length (as shot)	85 mm
Aperture	f4
Shutter speed	1/250
ISO	250
Distance from Subject	~1.5m
Image resolution (as shot)	5600 x 3728 pixels

Image resolution (final)	5163 x 3032 pixels
External Flash Model	Godox VING V860IIN
Flash Setting	Manual
Flash Output Power	1/16
Flash Distance from Subject	Mounted on camera, ~1.5m
Field of View	15.8° horizontal, 10.5° vertical

These settings allowed for the only exposure to occur when the flash was fired, while any movement which occurred outside of the flash duration did not get imaged. This prevented streaking and motion blur in the image, keeping the captured water sheet extremely crisp. The shutter speed was set to the camera's maximum flash sync speed.

The image was lightly edited to improve the clarity of the water sheet. The image was cropped to draw attention to the water. The highlights and shadows were adjusted in Darktable using curves and the tone equalizer to try and keep the background dark and the water sheet bright and well defined. The original unedited image is shown below in Figure 3, along with the final image for comparison.



Figure 3: The original, unedited image (left) and the final image (right).

Conclusion:

Overall, this image reveals the flow physics occurring when riding a bicycle in wet conditions. The spray of water kicked up by a wheel begins as a thin sheet adhered to the bike tire, then breaks up into smaller streams and droplets as it is flung off of the wheel. The high speed at which the wheel rotates causes this break-up to occur very quickly, and the process is almost impossible to notice with the naked eye. This rapid break-up can be explained by the high Weber number, We , of the flow. The author's favorite detail of the image are the curved ripples in the sheet, showing the effect of the water's adhesion with the tire as it rotates. Going forward with this flow setup, it would be interesting to examine the holes forming within the

sheet. Taking high-speed video or using a camera with a high burst rate could allow one to track the holes as the flow evolves. It would be interesting to discover if the holes originate at the water/tire interface and travel down with the flow, or if they form in the middle of the flow as part of the break-up process.

References:

- (1) Peakall, J.; Warburton, J. Surface Tension in Small Hydraulic River Models - the Significance of the Weber Number. *Journal of Hydrology (New Zealand)* **1996**, 35 (2), 199–212.
- (2) The Engineering ToolBox. *Water - Density, Specific Weight and Thermal Expansion Coefficient*. The Engineering Toolbox. https://www.engineeringtoolbox.com/water-density-specific-weight-d_595.html (accessed 2026-10-05).
- (3) The Engineering ToolBox. *Surface Tension*. [www.engineeringtoolbox.com. https://www.engineeringtoolbox.com/surface-tension-d_962.html](https://www.engineeringtoolbox.com/surface-tension-d_962.html) (accessed 2026-10-05).
- (4) Binnie, A. M. The Stability of a Falling Sheet of Water. *Proc. R. Soc. A* **1972**, 326 (1565), 149–163. <https://doi.org/10.1098/rspa.1972.0002>.