Force on a Highline Caused by River Flow[1]

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Abstract

Seattle Mountain Rescue (SMR) has been requested to rig and run highlines to hold divers conducting searches in rivers and to recover bodies from rivers. We know that water can exert large forces on objects, and we decided we needed to do some analysis to help us figure out what situations would be have acceptable forces and what configurations would have unacceptably large forces. SMR rigged a highline across a river, measured the speed of the river flow, held several variations of a boat and diver in the river, and measured the force exerted on the highline by the pull of the river on the objects held by the highline. Engineers tell us that the force of a current on an object is the velocity of the river, squared, times several other factors that don't change much as the river speed changes. Thus if we measure the force of a river pulling on an object, and measure the river speed, then we can calculate the force the river would apply at other river speeds. Our testing shows that in currents up to about 6 miles per hour (which is approaching whitewater conditions), when holding a rescue boat and single diver in the water, the tension on the track line that has a 30 degree deflection angle does not exceed 3 kN (675 pound). When the load is not moving, we consider 3 kN to be the maximum acceptable tension on the track line of a highline where a single 11 mm low-stretch rope used as the track line. At higher river speeds, it may be possible to limit the tension on the highline by increasing the deflection angle of the highline, or by reducing the cross-sectional area of the objects in the water. We recommend considering the consequences of failure of the track line: will a person be swept into a strainer or hazardous hydraulic? Can the system be rigged so that a system failure results in the load being pendulumed safely to a pre-determined bank of the river? This testing is preliminary and we recommend that others conduct further testing.

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[2] Date collection was organized and managed by Stephen Allen of Seattle Mountain Rescue. Other participants in testing were Bob Boyd, Bill Davis, Darren Emmons, Rich Evans, Doug Hutton, Jackie MacColman, Scott MacColman, Shawn Wagner, and Lewis County Sheriff dive team.

Introduction

Multiple times during the past two years Seattle Mountain Rescue has been requested to rig a highline across a river and either perform an extraction above the river, or to hold a boat in the river for a search or recovery. We know that rivers can apply large forces to objects in the water, and we know that the tension in the track line of a highline can become large. Our rigging systems are designed and tested to deal with hanging loads and shock loads from falls, not the pull of a river current. We realized that we needed more information to be able to judge what combinations of rigging and river currents would be reasonably safe.

We began with an internet search. We were not able to find much information in rigging, rescue, or boating literatures. We did find one set of numbers for force of river current on a body and a swamped boat. These numbers were repeated in four different documents, but we could find no information about how those numbers were generated.

Civil engineering has equations for calculation of the force on an object caused by fluid flowing around it. These equations apply to a river current flowing around a boat or diver being held in the river. By measuring forces in a slow river, we can use these equations to calculate how forces will rise as river flow speed increases. Existing work by many other people and groups addresses rope highlines and gives us guidance on acceptable loads on our highline systems. Combining all these parts, we can make some general judgments about whether our highlines can hold the objects we are asked to hold, in a particular river current.

Key Terminology

Throughout this paper we use two key terms:

> **River load:** The sideways force applied by flowing water against an object in the water. In other words, the amount of force needed to hold an object against the flow of a river.
>
> **Highline tension:** The tension in the track line rope of a highline system.

The Tests

The numbers reported here were measured using a highline across the Cowlitz River, in Lewis County, Washington, in mid-May, 2009. Members of several Washington State search and rescue organizations participated in the work. Earlier use of a highline to hold an inflatable boat on the Nisqually River, in Thurston County, and on the Green River in King County, Washington, helped formulate the questions and data gathering.

A relatively straight section of the river was selected as the test site. A highline was anchored to trees on opposite sides of the river, so that the highline stretched across the river (Figure 1). The anchor trees were selected so that the track line was very close to perpendicular to the flow of the river in the middle of the highline.

Figure 1. Testing configuration of highline across river and tethered boat.

Photo © Stephen Allen.

An inflatable boat was attached to the traveling pulley on the highline. A load cell was placed in the line that tethered the boat to the highline. Tag lines were used to position the boat in the middle of the highline span, near the middle of the river. Forces of the river pulling on the boat (plus any other objects attached to the boat) were measured by the load cell. A second boat was used to add and remove people from the test boat.

The flow speed of the river was measured by establishing two sight lines across the river, perpendicular to the flow of the river. These lines were located 200' apart, so that an object floating in the middle of the river traveled 200' as it traveled from the first sight line to the second sight line. The time it took an object to float from one sight line to the other was measured. The float time was used to calculate the speed of the river flow. The flow rate was 1.82 miles per hour.

Testing involved setting up several permutations of boats, passengers, divers, and inanimate objects in the test boat, and in the river tethered to the test boat. Because this testing was motivated by requests that SMR assist in holding a diver tethered to a boat while that diver does a search or recovery, we tested a variety of configurations that could possible occur during a search and recovery.

Results

The observed river load forces were low, ranging from 21 pounds (0.09 kN) for a boat with two passengers, up to 108 pounds (0.48 kN) for a boat with two passengers holding two divers in the water behind the boat. Note that these reported river load forces are the force that the boat pulls sideways on the highline system, not the tension in the track line of the highline system. This is exploratory research and we made no attempt to do multiple measurements of each configuration. We hope that future work will measure forces at other river speeds.

Table 1. River load data.

Load (lbs)	**Load (kN)**	**Load Factor**	**Configuration**
21	0.09	6.34	Boat w/ 2 persons
37	0.16	11.17	Boat w/ 2 persons & 1 diver on river bottom (approx. 15ft)
53	0.24	16.00	Boat w/ 2 persons & 1 diver on surface beside boat
53	0.24	16.00	Boat w/ 2 persons, towing litter like a sail at bottom of river
54	0.24	16.30	Boat w/ 2 persons & 1 diver behind boat
63	0.28	19.02	Boat w/ 2 persons & 1 diver underwater
65	0.29	19.62	Boat w/ 2 persons, 1 diver underwater & 1 on surface beside boat
75	0.33	22.64	Boat w/ 2 persons pulling diver up to surface
88	0.39	26.57	Boat w/ 2 persons & 2 divers on surface
98	0.44	29.59	Boat w/ 2 persons, towing litter like a sail in the water
106	0.47	32.00	2 boats w/ 3 persons in each boat
108	0.48	32.60	Boat w/ 2 persons & 2 divers behind boat

Calculating Forces for Other River Speeds

Civil engineers have developed equations for calculating the force of a fluid flowing around an object. In general, these equations can be distilled down to:

$$\textit{Force} = \textit{Area} \times \text{(other factors)} \times \textit{Velocity}^2 \qquad \text{[Equation 1.]}$$

Where *Force* is the force of the river flow on an object, what we call the "river load." *Area* is the cross-sectional area of the object relative to the river current. *Velocity* is speed of the river flow. The other factors include the density of water, the coefficient of drag of the flowing material across the object, and other things. For any particular object, these other factors don't change much as the river flow speed changes, so we don't need to know the value for each factor.

Knowing this relationship of river current force and velocity, for a particular object we can measure the force at one river flow speed, and calculate the force on that object for any other flow rate.

Notice that the weight of the object being held in the river is not part of the equation. The weight of the object being held is not part of the equation because—unlike a highline that holds an object suspended in the air—the highline does not hold up the object. The water holds up the object, and the highline holds the horizontal pull of the current.

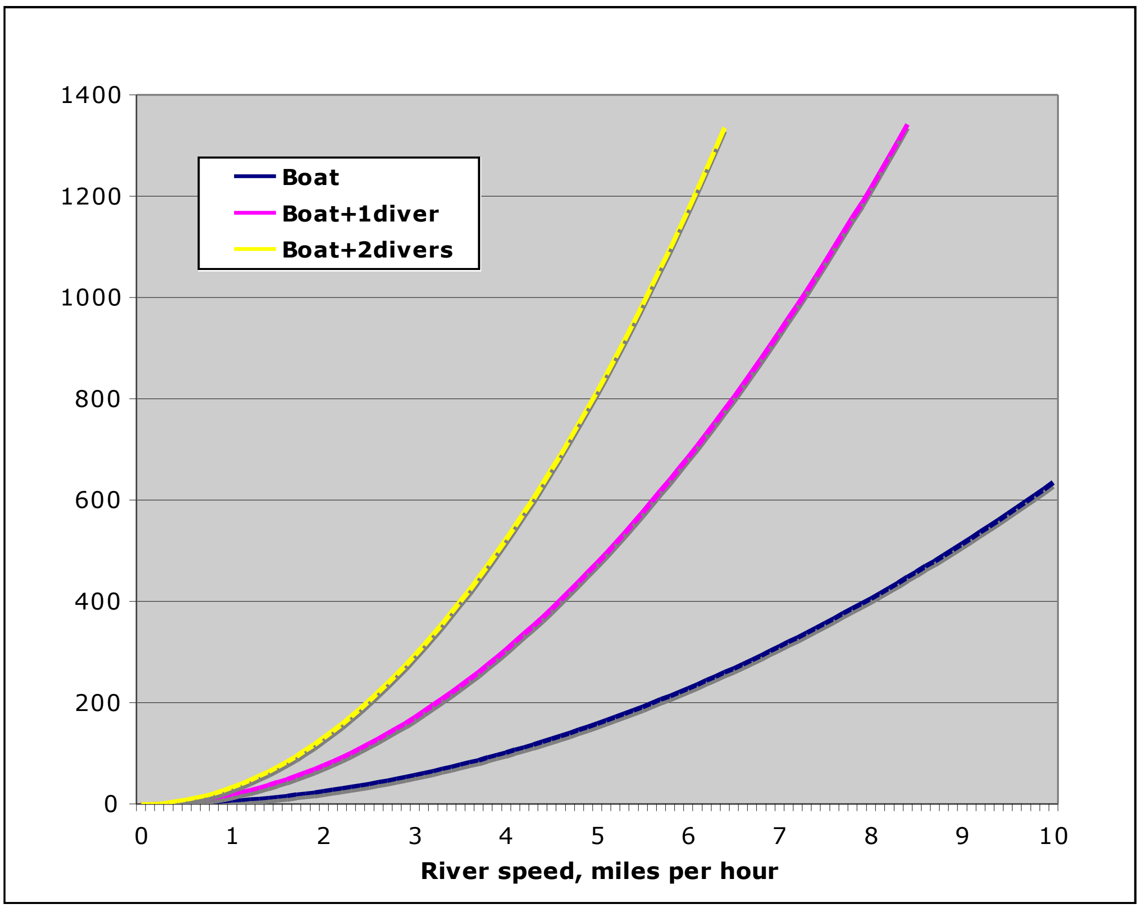
We want to predict the force, or river load, at different river velocities. To do this, we simplify the equation by combining the area of the object and all other factors other than velocity into a single term that we call the "Load Factor." Each object or configuration of objects has its own load factor. The load factor for a particular object remains relatively constant as river velocity changes. In theory, there is some change in the factor, and eventually the flow would become whitewater or would cavitate around the object in the water, and the load factor would change. However, we make the simplifying assumption that the load factor is constant across river velocities.

Using algebra to re-arrange the terms of Equation 1, we find that:

$$\textit{Load Factor} = \textit{River Force} / \textit{Velocity}^2 \qquad \text{[Equation 2.]}$$

Calculated load factors for each configuration we measured are reported in Table 1. A different boat (or other object) will have a different load factor.

Figure 2. River loads as a function of river speed, for selected configurations.



We can take the load factors we calculate from our field measurements, and insert them into Equation 1 and calculate the river loads for different river speeds. Figure 2 shows the results for three representative configurations, (1) a boat with two passengers and nothing else suspended in the water, (2) a boat with two passengers plus one tethered diver in the water, and (3) a boat with two passengers with two tethered divers in the water. These configurations include the configurations with the highest (boat plus two divers) and lowest (boat with nothing in the water) river forces that we measured.

We do not have rules of thumb for classifying river flow rates. Searching the internet and talking to river experts has not yielded much guidance. Apparently, flow rates less than about 2 miles per hour are considered relatively slow, and fast-flowing rivers where it would be very difficult to stand in waist-deep water seem to have speeds of about 3-4 miles per hour. Whitewater seems to have speeds above about 6 miles per hour. But we caution that these estimates are provisional. Still, it appears that holding an inflatable boat and a diver in the water would cause an acceptable load on a highline in flows less than whitewater (but perhaps not an acceptable load for the diver!).

Using these Results

The main purpose of this research is to be able to limit the load on a highline such that there is an acceptable tension in the track line of the highline. Limiting the tension in the track line should result in the highline performing as intended, which should result in the system holding the load in the intended position, or moving the load along the intended course.

Standard analysis can be used to calculate the tension in a track line as a function of the load, and the angle that the track line is deflected from straight. Repeating standard principles that many of us have already been exposed to, a (theoretical) perfectly straight highline would have infinite tension, even under a small load such as the weight of the rope. With 90° deflection, which would be a bight of rope hanging down, half of the load is held on each side of strand of the bight, which means that the tension in the track line of a "highline" with a 90° droop angle would be half the load. However, such a "highline" would have no span. To limit the tension of the track line to a reasonable force, while having a reasonable span, and to keep a load suspended, highlines in rescue situations often have deflection angles between 15° and 30°and almost never exceed 45°. The tension in the track line of a highline, as a proportion of the weight of a load suspended in the middle of the highline, is given in Table 2 for selected deflection angles.

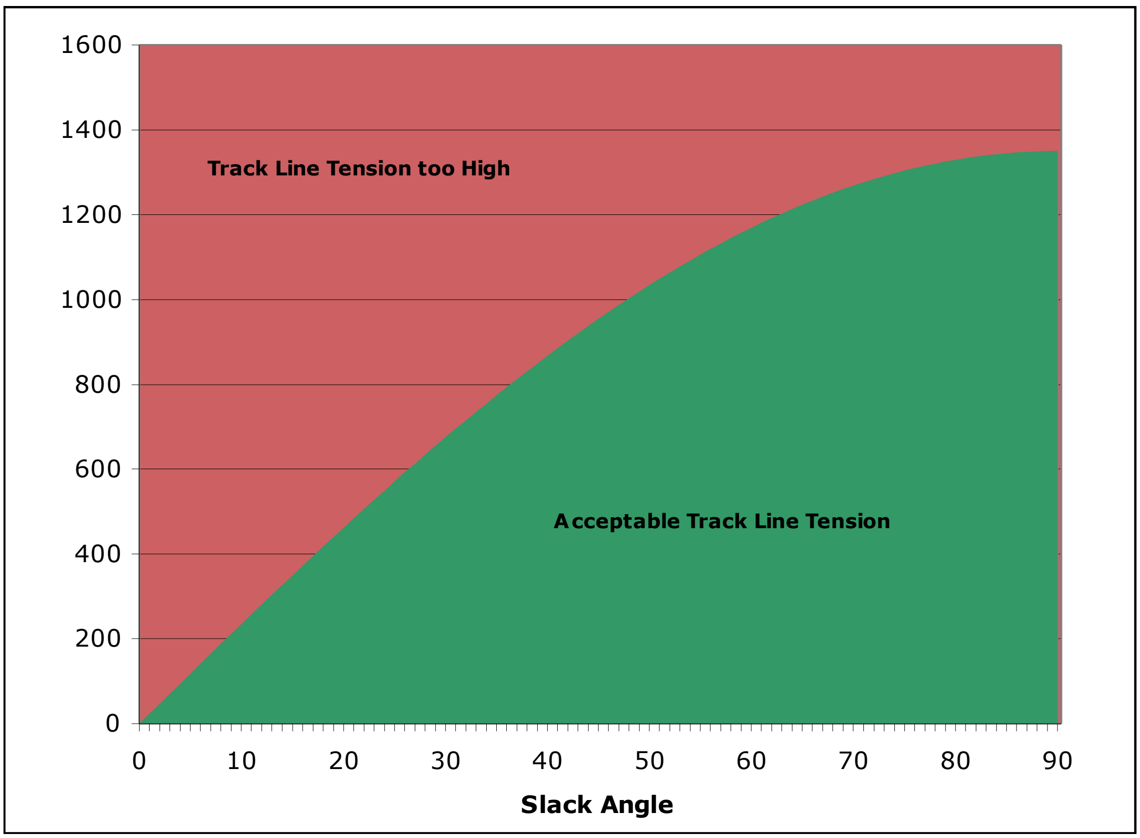
Table 2. Maximum permissible load to keep track line tension to no greater than 3 kN (675 lbs) for selected track line deflection angles.

Deflection Angle	**Track Line Tension (proportion of load)**	**Maximum Load (pounds)**	**Maximum Load (kN)**
45°	0.72	955	4.2
30°	1.00	675	3.0
15°	1.93	349	1.6
10°	2.88	234	1.0
5°	5.74	118	0.5

A highline used to hold a boat in a position in a river is functioning differently from a highline used to suspend a load in the air. The highline holding a boat in position will not experience a shock load from a fall, because the object attached to the highline is already being held up by the river. However, the highline in the river application could experience a large increase in load if the cross-sectional area of the load (relative to the direction of flow of the river) increases, such as would occur if an attached boat were to become swamped, or floating debris were to entangle the boat.

Because a highline over a river is functioning differently than a highline holding a load in the air, we do not know what would be an appropriate safety factor for the normal load. In the absence of knowing an appropriate safety factor, we use the factor that we use for a highline in a typical rescue situation, that the tension in the track line should not exceed $1/10^{th}$ the breaking strength of the system, where a high strength tie-off is used to anchor the track line. This safety factor yields 3 kN (675 lbs) as the maximum tension, when the load is not moving. With this maximum tension, we can calculate the maximum acceptable river load for any particular track line deflection angle. This relationship is graphed in Figure 3.

Figure 3. Track line deflection angles that keep track line tension to no more than 3 kN (675 lbs), as a function of river load.



Concerns and Warnings

The equipment and rigging configurations we use in mountain rescue were designed for and tested in terrestrial situations. The ropes are designed to limit shock loads by stretching. Stretch could be a bad thing in a river application, if it allows a diver of boat to get trapped by a hazard or to go over a waterfall. Consider what would happen if the rigging system stretches, and whether this situation would be acceptable.

If using a terrestrial highline system to hold a load in flowing water, we recommend extra consideration of what might happen if the system is overloaded and fails. Would it be desirable to attach the load to the highline with a link of limited strength, so that if the load is entangled the link will break? Can the occupants of the boat or divers cut themselves free and float or swim to safety? If there is a hazard downstream, and if there is room for the load to pendulum to one shore, would it be desirable to anchor the track line rope on the opposite shore with prusiks that will fail at moderate force, allowing the load to pendulum to the side of the river? If this approach is used, the track line on the releasing side must also release.

This analysis considers only the force required to hold an inflatable boat and divers in a river, as the river speed varies. It says nothing about the reasonableness of being in the water in the first place. Anyone using this research should have swiftwater skills and use their own judgment to make sure that they keep themselves safe.

Conclusions

Conclusions useful to rescuers are:

- Divers and inflatable boats held in a moderately slowly flowing river resulted in small loads on the highline system.
- River loads start increasing quickly as river speed becomes fast; but it may be acceptable to hold an inflatable boat and one diver in river speeds approaching whitewater flow speeds.
- Consider limiting the size (cross-sectional area) of the load, especially if river flows are fast and if objects are going to be held while they are submerged in the water.
- Having a large deflection angle in the highline—such as greater than 30°—minimizes the tension in the track line.
- Consider what could go wrong, and how this could affect the system and the people on the system.

This research is preliminary. We expect that further research will reveal things that we do not anticipate here. Every object is different, and will have different behavior in flowing water. We recommend that each group do its own testing before performing any particular rigging activity where the load might touch flowing water.