Highline Rescue Boat Systems:

A study of the load created by tethered rescue boats with respect to stream velocity, trim and hull size.

Chris Onions

A thesis submitted in partial fulfilment for the requirements for the degree of MSc by Research at the University of Central Lancashire

April 2013

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ABSTRACT

Water rescue practitioners must balance the degree of risk associated with a given technique with the needs of the victim. One such technique, the focus of this study, consists of a rescue boat positioned within moving water by means of a high line. It has been shown to be useful for high risk rescues, often when the patient or subject is unable to assist with their own rescue. Despite the degree of risk, little empirical data pertaining to the resulting load (force) placed on the highline by a boat in moving water can be identified in the literature.

In the absence of contextual data, this study examines the research undertaken by the rope rescue community into the forces exerted by suspended loads, and argues that many of the resulting principles, especially the establishment of the load, are not applied during highline positioned boat operations. Therefore the research question of this thesis; ‘what force (N) will be induced by a boat positioned from a high line when deployed in moving water typically encountered during swift water rescue?’ is addressed by establishing the load under real-world operational conditions. In addition to this, the antecedents leading to a proposed worst case event (WCE) are also presented, and tested.

Testing was conducted within a flow-calibrated channel offering stream velocities typical of those encountered during water related rescues. Two contrasting craft were selected for the investigation as representative of those used during swiftwater rescues, a Eurocraft (large hull) and an MFC Rescue Sled (small hull). The experiment subjected the high line to a range of forces induced by the two craft over a range of stream velocities between 0.6 – 5.4ms^{-1}. A load cell was utilised to collect force/time data during deployments to the current vector. The independent variables of trim (relative positioning of the load within the boat) and average stream velocity were investigated.

Under low flow conditions, when trimmed neutrally (the crew were positioned centrally), the Eurocraft induced the *highest* force on the high line (approximately 1.22kN at 0.6 ms^{-1} average stream velocity). When trimmed with the load placed to the rear (aft) or towards the front of the boat (bow trim) force was reduced on the high line. Conversely at higher stream velocities (4.5 – 5.4 ms^{-1}) force values rose rapidly when bow or aft trim conditions were induced, and force was reduced in a neutral trim state.

The testing of the WCE induced a peak force of 3.42kN when the boat was deliberately flooded with water during the highest flow available (5.4 ms^{-1}). The force associated with the WCE for a high line constructed with a track line mid-point angle tending to >120º is a theoretical force multiplication approaching that of the rating of the equipment.

CONTENTS

Acknowledgements

I would like to show my gratitude to Paul O’Sullivan, General Manger of Rescue 3 (UK) Ltd, my supervisory team at UCLAN; Bryan Jones (Director of Studies), Nigel Garratt and Iain Adams. To the swiftwater rescue technicians Rob Litherland (Rescue 3 UK) and Dan Graham (Rescue 3 Europe), Simon White (Manager of TBIWWC) and his staff Chris Walker, Tom Tindale and Luke Duddles without whom it would have been impossible to conduct this study.

1.0 INTRODUCTION

Water rescue practitioners have defined a range of techniques assembled into a hierarchy of risk. For field expediency, an easily memorable phrase – *talk, reach, throw, row, go/tow, helo (sic)* has been described by Rescue 3 (Edwards et al. 2010) to assist practitioners to select the appropriate technique from the range of techniques during incidents when time is often critical. The range of options commence at the low-risk end of the spectrum with a rescuer offering assistance from the bank-side by coaching the victim to swim to safety (*talk*), offering a extended pole or improvised reaching tool, for example a paddle (*reach*) and throwing a specifically designed throw- bag containing floating line (*throw*). The remaining three options require the rescue practitioner to either enter the water or to access the casualty from above the water by means of a load-suspension system. The rescuer may attempt to offer assistance by accessing via a boat (*row*), adopting a specialised tethered swimming technique (*go/tow)* or via helicopter (*helo).*
Although the range of rescue solutions has been presented as a hierarchy, Rogers (2010) has stated that ‘It is the victim that makes the decision for the rescuer.’ This statement is a reflection of the condition of the casualty, possibly exhausted, hypothermic and having endured periods of submersion that will determine (with other environmental and Agency capability considerations) the appropriate rescue technique that should be deployed. Therefore, following Rogers’ premise, both the risk and the needs of the patient must be balanced during the decision making process.

Of the range of options described briefly above, it is the *row* option that is the subject of this thesis. Often the flow of water may be so strong that an inflatable raft cannot be positioned by paddling alone. During the extrication of a casualty located on an obstruction in mid-stream (for example a rock or vehicle) or from a retentive hydrological feature (hydraulic jump, page 5) fine positioning of the craft against the flow of water, referred to as *holding station* is desirable. Under these circumstances the craft may be positioned by virtue of a system of tensioned ropes rigged across the moving water so that the craft is positioned accurately. A common set up is shown in Figure 1, illustrating a technique in common use internationally, hereafter referred to as a *boat on a high line.* Specifically this technique employs the use of a *Norwegian reeve* facilitating the positioning of the craft up or down stream and a tensioned line, along which a carriage positions the craft toward the left and right hand sides of the river.

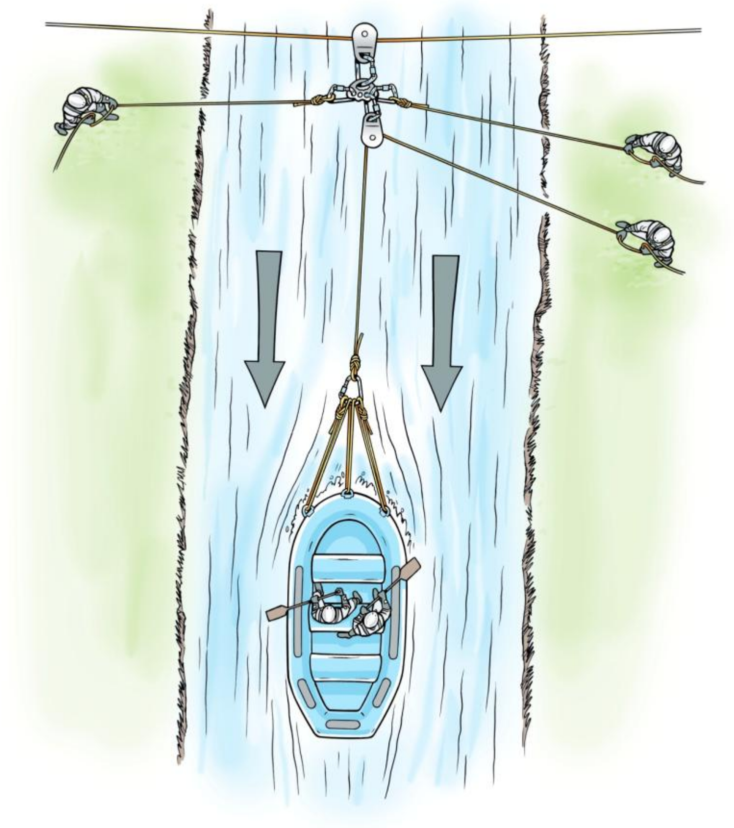


Figure 1. Boat on a Highline. Image by George Manley, courtesy of Rescue 3 (Europe).

The literature reviewed during the preparation of this thesis describes many instances (often with rescuer fatalities) when such a technique would have been preferable to either motorised or crew-paddle positioning of the craft. The literature also describes methods (including case studies) by which the risk posed to both members of the public and the rescue community may be reduced by the removal or modification of hazardous water features at source.

Analogy is drawn from the developers of mountain rescue techniques utilising a high line to position a rescuer above a span, often above water. To draw distinction with the boat on a high line technique, the mountain rescue high line is hereafter referred to as an *aerial high line*. The developers of the aerial high line realised that they needed to establish the static load on a tensioned line, and propose a worst case event (WCE) which systems may feasibly be subjected to. By reproducing the WCE under real world testing conditions and therefore identifying the resultant peak force, operational guidance including a recommendation of the system rating (force) could be established. While the work of mountain rescuers and swiftwater rescuers is often aligned (for example the Mountain Rescue community in the UK has both a mountain rescue capability and an emerging swiftwater rescue capability) (Thomas, 2012) little material could be found in the literature of a similar line of enquiry to establish the force subjected to a boat on a high line by moving water. Therefore it is conjectured that water rescue agencies and water rescue training providers alike are unable to rate their systems and provide appropriate safety factors accordingly. Therefore, this thesis presents the research question;

> “What force (N) will a boat typically encounter when placed upon a high line and deployed in moving water during swift water rescue?”

By testing 4 hypotheses and by re-creating the conditions associated with a proposed worst case event, force has been recorded when boats of two contrasting sizes are positioned by a high line in representative, but controlled, real-world conditions. The hypotheses formulated include the influence of trim (positioning of the load within the boat), the size of the hull selected and the stream velocity of the water in which the boat is operating. Comparisons have been made with other related fields from within the literature to contextualise the derived data.

This thesis is presented as an initial step to understanding the load on (and consequences of overloading) a high line system when utilised to position a rescue boat within moving water. The method by which the results were obtained, and the results themselves are presented for scrutiny and peer review. Further testing and validation must take place before rescue agencies embed the findings within their own training and operational guidance.

While this research is concerned with the specific details of the high line rescue boat, it is set within the context of the development of the national flooding enhancement project in the UK, facilitated by DEFRA (Department for Environment, Food and Rural Affairs, 2010). This framework attempts to establish a common understanding of capability by agencies responding to national water incidents.

It is hoped that the results of this research will be the first step to produce working guidance associated with empirical data in this field. Steve Glassey (personal communication, February 2013) considers that 'there is an overwhelming requirement to incorporate evidence - based practice into our teaching rather than recite someone else's gospel.' Such an evidence base (albeit embryonic) may prove useful to Incident Commanders faced with making a professional judgement during a rescue to which a tethered boat could be an option.

2.0 LITERATURE REVIEW

2.1 Hazards in Moving Water

Rescue practitioners have refined methodologies to resolve a diversity of water related situations, especially those involving hydrological features that retain or entrap a victim, sometimes mid-flow in a moving water body. Such features are described as *re-circulating*, and given the colloquial name of *stoppers* by the rescue community (Ferraro, 2006: 29), more correctly termed *hydraulic jumps* by hydrologists and hydraulic engineers (French, 1986).

A hydraulic jump is induced when a structure (manmade or natural) obliges a flow of water to reverse its direction, so that the surface velocity appears to the observer to be against the gradient. When this feature is maintained at the foot of an obstruction in the river such as a boulder, spillway or low-head dam it is termed a *submerged hydraulic jump* and is characterised by a full-depth re-circulation. The first person to record such an observation of a hydraulic jump was Leonardo da Vinci, (Rouse and Simon, 1957: 25) but it was not until the 17th century that Borden first formally described the hydraulic effect, thus producing the foundation text on the subject (Bidone, 1818).

A common, modern design requirement of weirs, spillways and low head dams is to induce a *submerged* hydraulic jump to control excessive kinetic energy of flowing water downstream of the structure (Sholichin and Akib, 2010). A stilling basin installed at the base of the dam induces a portion of the water to re-circulate back up stream towards the face of the dam (Forste and Skrinde, 1950). The recirculation causes buoyant objects to be pushed beneath the surface at the dam face to the base of the stilling basin, and then back to the surface and drawn towards the face of the dam whereby the cycle is completed (Ray, 1997: 163). Should a victim fall into the jump, this re-circulation will occur almost indefinitely or until either a rescue takes place, the water level drops (weakening the retentive effect) or the feature becomes *drowned out* by a rise in the water level upstream of the feature. Not all hydraulic jumps are deemed to be hazardous however. If the jump re-circulates water at the surface only, it does not demonstrate full depth recirculation and can offer recreational kayakers a *play or surfing* wave (Matt, 2002: 286). The features of a non-hazardous hydraulic jump are a shallow ramp angle, short tow back and aerated water. Conversely, many man-made features *are* hazardous due to their retentive nature, their remoteness from shore, leading to the helpless condition of the Subject. Rescuers are often obliged to implement a tethered boat technique to execute the rescue under these circumstances.

Tethered boat techniques have been devised by rescue training agencies and rescue organisations to prevent a rescue boat from being drawn into a hydraulic jump. As described below, the literature details numerous historical events where self powered rescue craft, in an attempt to manoeuvre close to the victim, hold a stationary position relative to the land close to the boil line (the demarcation of the hydraulic jump and the outflow). Any error or miscalculation by the helmsman will result in the boat being moved into the reverse current and swamped by the outfall at the dam face.

In September 1975 an incident at Binghamton, New York on the river Susquehanna resulted in the death of three rescuers and a further four injured casualties (Elverum and Smalley, 2008). The river level was unusually high for the time of year when a raft containing two people floated over the dam and became trapped in the re-circulating current at the base of the dam. Three fire-fighters attempted to assist in a self powered rescue boat (not tethered) which also capsized resulting in the death of one of the fire fighters. The remaining two fire-fighters and the two original victims from the raft survived. The following day, an attempt was made to recover the body of the fire-fighter (still retained in the re-circulating water of the low head dam) using a self powered rescue boat (again without tethers). This boat also capsized at the base of the dam, resulting in the three fire fighters being thrown into the hydraulic jump. Yet another self powered rescue boat was launched, but already two of the fire fighters had drowned. Observation of historical news footage (Wenck, 2012) of some of the rescue attempts at Binghamton show that the face of the dam was relatively low due to the unseasonably high water levels, and so the submerged hydraulic jump may have looked to the untrained observer to be innocuous. It was also clear from the observations how quickly and inexorably an un-tethered boat is drawn towards the dam face once it crosses the boil line. This event is the first recording of the term *drowning machine,* now in common use amongst rescue professionals and public safety campaigners, for example (Wright, Earles and Kelly, 2004) and (Elverum and Smalley, 2008) that the author can identify in the literature. The hazard that such features present to the public and rescue community is significant (Horst, 2010). Observations made by rescue training providers suggest that a tethered boat methodology at Binghamton would have been difficult to implement as long lengths of rope (300 – 600m) would have been required (Bills, et al. 2011: 63).

2.2 Removing the threat at source: Low head dam removal

Reduction of the degree of hazard posed by low head dams at source would reduce exposure of risk to the public and rescue personnel. The removal of redundant low head dams to reduce the risk to the community is however often contentions

(AASHTO, 2005). The detrimental effects of sediment release on downstream flora are discussed by Chang (1998: 432), decreasing the amount of water impounded upstream (Morris and Fan, 1998) and increased flood risk (Shafroth et al, 2002). Therefore it is not always possible or practical to remove low head dams, so In the UK weir modification is often prioritised on a basis of risk, for example weir X on the River Tryweryn, North Wales (Davies, 2010) and numerous weirs on the river Thames (Arcadis, 2010).

The basis of weir removal is a consideration of both public risk and risk to the rescuer who has been called to assist at a weir related incident (Paul O'Sullivan, personal communication, July 2011). From a public risk perspective, factors to be investigated should include; signing, railings and any protection offered by a boom on the up-stream side of the weir. In the weir specifically, the flowing are considered; presence of vertical retaining walls at the sides of the re-circulating hydraulic that pre-empt escape from the feature, the size of the hydraulic jump (called the tow-back) and if there are any weaknesses in the re-circulating hydraulic that would 'flush' a swimmer to the downstream side of the retentive feature. The rescuer – risk evaluation considers if access is available to personnel and vehicles, if anchors are available from which to construct a boat high line system and the presence or absence of over head wires for a helicopter based rescue (O'Sullivan, P. and McKay, C. 2009).

2.3 Dam modification

Observations made in the pioneering work to educate hydraulic engineers to the hazards posed by re-circulating hydraulic features to the wider public and recreational boating community include Leutheusser and Birk (1991) who refer to the re-circulating water (hydraulic jump) as a 'vortex';

> ‘The vortex is commonly called the hydraulic by canoeists and water safety experts who fear and respect its potential to maim and kill, yet the phenomenon is virtually unknown in the hydraulic engineering literature.’

The authors advocate the incorporation of a cascading baffle to eliminate the conditions required to form the submerged hydraulic jump. Other forms of modification to low head dams have been identified (Wright, Earles and Kelly, 2004) including horizontal deflectors, slope grading with rock fill and the construction of downstream ledges.

Modification of existing structures, or the complete removal of low head dams, combined with public education programmes represent a proactive approach to public safety. In the interim, rescue agencies continue to train to effect rescues as required. Although not an exclusive solution, currently common practice by rescue agencies suggest that tethered boat rescue systems will be implemented for river rescues involving submerged hydraulic jumps.

2.4 Implications for Rescue Agencies

From a national strategic perspective, the framework for water rescue first responders is laid out in the National Flood Enhancement Project; Concept of Operations (Department for Environment, Food and Rural Affairs, 2012). Water Rescue Technicians are required to have a working knowledge of hydrology (for example hydraulic jumps) and to be able to implement tensioned rope rescue systems (boat on a high line).

At a tactical level, in the UK, a weir risk evaluation procedure has been published (O’Sullivan and McKay, 2009) which assists both weir operators and responding rescue agencies to score the level of hazard for a given weir within their jurisdiction. This assessment considers the practical implications of conducting a boat on a high line rescue from a weir, including span distance, height above the feature, vehicular access and the provision of anchors (necessary for constructing the high line). Rescue 3 training courses (Bills, et al. 2010) describe a range of rescue operations culminating in a helicopter rescue as the highest risk option. Many rescue agencies (for example Nottinghamshire Fire and Rescue Service) include the request of a search and rescue capable helicopter to attend low head dam incidents as standard operational procedure (M. Bills, personal communication, February, 2012). Helicopter rescues from low head dams should not be undertaken lightly however. For example, A. Lee (personal communication, May, 2012) reported significant debris present in the re-circulating hydraulic jump in the Elwis street weir on the river Don at Doncaster during the recovery of a victim. The debris (consisting of railway sleepers, gas cylinders and timbers presented a significant risk to the Winchman of an RAF Sea King deployed to recover the victim from the weir. (Taylor, R, personal communication, May, 2012).

Helicopters may also be subject to mechanical failures and may not be operable during periods of poor weather and limited visibility (Sq. Ldr S. Wright, personal communication, May, 2011). Therefore, winch capable aircraft do not present a default-option for recue agencies, and so, in the absence of a helicopter, a tethered boat may be the only option for a rescue or recovery from a low head dam or similar feature.

2.5 Tethered Boat Rescue – Boat on a high line

The boat is tethered such that the bow faces up-steam to a pulley connected to the highline (Figure 1, page 2). The boat may be positioned across the width of the river (*x axis*) via the tag lines, and up or down stream (*y axis*) by a secondary reeve system (Figure 2). Further lines connecting the stern of the boat to each bank stabilise the craft in turbulent flow.

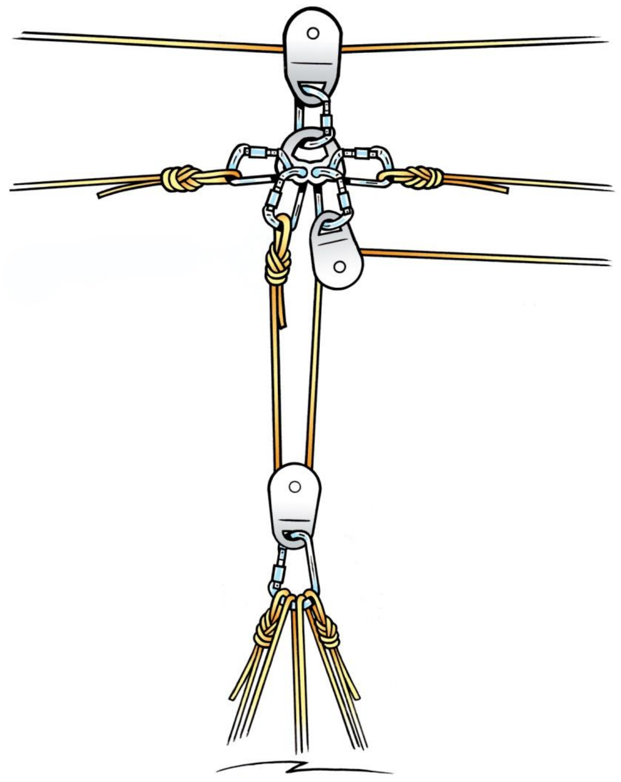


Figure 2. Norwegian Reeve. Image by George Manley, courtesy of Rescue 3 (Europe).

Positioning of the boat is achieved by careful communication between the helmsman and the bank based incident commander (Bills, et al., 2010: and Ray, 1997: 128) and may be fine tuned by the helmsman with a paddle.

A tethered boat represents a *high* risk to the rescue personnel, but offers a *true* type rescue to the casualty. A true type rescue is indicated when the casualty is not able to help themselves or may be unconscious (Bills, et al., 2011). A *conditional* type rescue is effective when the victims are able to behave appropriately and play an active role within their own rescue. Such rescue practitioners employ a progressive intervention strategy from low to high risk, and the optimum choice is the method that exposes the rescue team to the least risk while providing an effective rescue of the casualty (Edwards, et al., 2005:12).

The tethered boat employs a chain of components, each of which is manufactured to a standard within Europe. Rope selection normally includes low stretch kernmantel rope (British Standard, 1998), karabiners (generically termed connectors) (British Standard, 2004) and pulleys (British Standard, 2007).

Although the individual components of the rescue chain are well understood and documented, little is known about the actual force placed onto the system when deployed onto moving water (P. O'Sullivan, personal communication, January, 2010). The boat may be subjected to a force produced by the flow of water moving downstream, and also by re-circulating water upstream. The boat may even experience a sheer force when it crosses the demarcation between downstream flow and re-circulating water (Ray, 1997: 165).

Findings presented by rescue practitioners (Smith and Stephen, 2009) detailed their in-water; real world analysis of the forces placed upon a highline by a diver, positioned in a river flowing at 6 miles per hour (2.7 m/s) induced a force in the high line of 3 kN. This value would be at 1/10 of a system constructed to withstand 30kN (10:1 safety factor) which as we will see is a desirable characteristic to be considered when constructing high lines (page 14). The authors proposed a model, based upon their findings which predicted loads for a given water velocity and demonstrated how the force values increase exponentially with respect to water speed. The investigation was conducted in a river of flow 1.82 miles per hour (0.81 ms^{-1}) in which they reported low load forces (0.09kN for a boat with 2 people on board). The work was presented as 'exploratory' and they '...hope that future work will measure forces at other speeds.'

Another method of calculating the indicative force on objects tethered within moving current vectors is outlined by O'Shea (2006). O'Shea argues (personal communication, May, 2012) that the force induced by the water will be proportional to the change in momentum of the water incident to the surface area of the object within the flow. Newton's third law dictates that the water *pushing* upon the object will equal the *pull* in the ropes holding the object in the flow, so a representative model of the tension on the anchors and rigging ropes may be achieved. It is summarized in this context by the formula (1).

$$\text{Force} = \text{density of fluid} \times \text{velocity}^2 \times \text{area} \qquad (1)$$

While this method is simplistic, it is only applicable to objects incident (positioned at 90° to the water flow), and relies on linear stream lines rather than the turbulent flow encountered by practitioners in the field. The tubes or sponsens of a rescue boat will present a *curved* section to the flow, and it is feasible that they will change their shape when subjected to the pressure from the water flow. These uncontrolled variables make it impossible to compute a force value dependent upon surface area incident to the flow alone. For this reason it is argued that a real world evaluation of the forces will be more representative than a mathematical one, however, the formula presented by O'Shea (1) for calculating indicative forces will be used as a premise for the formulation and testing of hypotheses in this thesis.

2.6 Rope Rescue System Development

The British Columbian Council for Technical Rescue (BCCTR) was tasked in the 1980s to set standards for the Provincial Emergency Programme (PEP) relating to the performance of devices used to catch rescue loads (Dill, 1990 and Mauthner, 2005). One of the key outcomes was the proposal for the WCE that may occur during mountain rescue operations with suspended loads. The BCCTR proposed that the most complex phase of the operation when a failure is likely to occur corresponds to the situation in which there is the least amount of rope in service to absorb the energy generated by the failure. It was suggested that that the most critical phase of a rope rescue sequence is when the attendant moves the stretcher with patient from the horizontal ground - over the edge to the vertical terrain during a lower. This phase is known as the *edge transition.*

The BCCTR identified that there was a higher likelihood of failure during the edge transition due to the attendant struggling to manoeuvre the stretcher over the ledge. Proposed mechanisms of failure at this juncture include; edge lip failure, the initial loading of the system revealing an alignment error, equipment or anchor failure and a stumble by the attendant close to the lip of the edge (Gibbs, 2007).

These contributory factors of failure during the edge transition are especially important because there is very little rope between the load and the anchors. The BCCTR proposed that the attendant and stretcher could fall 1m, due to an Attendant stumble, or equipment failure with as little as 3m of rope in service to absorb the energy of the fall. This equates to a fall factor 0.33 (fall distance/rope in service) and would correspond to a theoretically high impulse force to which the patient, attendant and equipment would be subjected (Schubert, 1991:169).

The development of water-based rope rescue systems, especially the boat on a high line have evolved from rope rescue systems designed to accommodate a *suspended load.* The premise for incorporating a 10:1 static system safety factor (SSSF) in suspended load rope rescue systems is examined, and will influence the line of enquiry leading to the proposal of a safety factor for high lines designed to control tethered boats. The BCCTR achieved this within the field of rope recue during their examination and establishment of belay competence criteria.

2.7 Belay Competence Criteria

The BCCTR were in a position to formulate a standard by which belay capture devices could be evaluated within the context of the occurrence of a worst case event. The standard (ASTM, 2011) details the Belay Competence Drop Test Methodology which states that,

> *A rescue belay should be capable of catching a 200kg mass, representing two people, plus equipment falling 1m on 3m of 11mm rope, with no more than 1m additional travel distance (pre-rebound) and with no more than 12kN of peak force.*

The worst case event and corresponding set of belay competence criteria established by the BCCTR demonstrate a thorough and critical examination of the vulnerability of rescue systems. This is a fundamental model of enquiry to this study, as little evidence of a similar logical line of enquiry to tethered boat methodologies is evident. The proposal of a worst case event - specifically for tethered boat highline systems is made and tested.

2.8 Aerial High-lines

The principles behind the construction of a competent highline have been described by the British Columbia Council for Technical Rescue (BCCTR) (Mauthner and Mauthner, 1996). The BCCTR reviewed historical maritime shipping manuals, illustrations and even wood-cut images and concluded that there are some common generic principles that should be included within a modern aerial high line; These principles suggest that the tag ropes should be connected to the carriage (not the load, and a static safety factor should be included. The safety factor should be established so that should a dynamic event occur, then the integrity of the highline is not compromised. (General engineering philosophy describes a static safety factor such that the mean loading always falls at a value less than the mean strength *by a known factor* (O'Connor, 1985: 102). The system should include an element of *redundancy* should a primary component fail, then it is backed up by a secondary system and the system should incorporate a force limiting device to prevent over loading. This latter feature is analogous to a safety valve within a pressurised system or a slipping clutch within an automotive transmission system.

To manage the force in the high line, field techniques have been presented to control the track line tension. Frank (2010: 271) describes *a rule of 12* where the number of pullers multiplied by the mechanical advantage velocity ratio yields an indicative resultant force.

> If 2 people pull on a mechanical advantage of 6:1;
> Then track line tension ≤ 3kN.

By limiting the track line tension to ≤ 3kN, using trigonometry, the angle at the carriage will resolve to 160 degrees for a 1kN load. In the field this practice has been reported to work well (A. Read personal communication, March 2011).

The premise for maintaining track line tension at ≤ 3kN for a 1 kN load is that an acceptable 10:1 static system safety factor (SSSF) may be maintained (James, 2010: 272). This assumes that the un-knotted strength of the track line is in the order of 30 kN.

Further to the rule of 12 and the 10:1 SSSF described above, Mauthner (personal communication, May, 2012) advocates the inclusion of force limiting devices within the high line that prevent excessive loads being generated by introducing more rope (slipping) at a pre- determined value of approximately 7kN. Mauthner has developed a device (CMC Multi Purpose Device ™) specifically for this purpose (Frank, 2010:

131). There is also limited evidence that prusik hitches will tend to exhibit a tendency to slip within a range of 7 – 11 kN. For examples of the performance of prusik hitches see Kharns (2008) and for an evaluation of prusik compatibility testing see Onions (2011) and with Sterling 11mm rope (Jones, Read and Onions, 2012). The force in a tensioned rope track line with a force exerted at 90 degrees (the hanging load) is determined by the angle at the intersection (O'Shea, 2007). As it is impossible to observe this angle during application, the solution presented in the Kootenay system is to limit the input force, so the track line tension with a hanging load cannot exceed a given value (3kN). Regardless of the load placed on the highline at mid-span, the angle at the carriage will resolve according to a value predicted by trigonometry. It is worth looking within the literature for similar considerations when constructing tethered boat high lines.

2.9 Boat High Line Rescue

Slim Ray (Ray, 1997: 126-128) has described a continuum of tethered boat techniques, from a single point tether (managed with a single line), a two point tether, and a four point tether. All of these methods are suitable for river current velocities that allow the tethers to be *hand held* by the operators. The progression of the continuum ends with the high line system that offers fine control (and specifically) the greatest degree of security when operating near hydraulic jumps.

> ‘To ensure that the rescue boat does not get caught in the backwash, it has a couple of tag lines attached at the stern, tended from downstream of the boil line.’

This system utilising a tensioned track line and mechanical advantage, has been adapted from the high line principles used to extricate victims from narrow, linear features like river gorges where access is particularly difficult or for transporting personnel across rivers when bridges have become unsafe or collapsed during major flooding events. There are two variants;

- A *Dipping Highline* used when there is adequate height above the base of the feature to accommodate the associated stretch in the track rope
- A reeve highline (English or Norwegian) that allows the load to be lowered and raised from the highline.

Water rescue practitioners have effectively *borrowed* the technique from rope rescue specialists (P. O'Sullivan, personal communication, February, 2011). By changing from an aerial application to a water based one, many of the sound underpinning principles of the high line may no longer be valid, and it is conjectured that many assumptions have been made concerning the safety of the application.

It has been shown that operational field guidance has been established by the BCCTR to manage track line tension to an acceptable level within aerial high lines. This is based upon many system constants, namely the load which is proportional to the mass (kg) and the acceleration due to gravity (m/s/s). However these constants do not exist within the application of a high line to position a boat within a channel of moving water. In this context the load is proportional to many variables including the stream velocity and the shape and cross sectional area of the boat. The application of an aerial high line is based upon sound principles, and it is conjectured that such a basis is not evident in the case for a high line used to position a boat. A summary comparison of factors influencing the load is presented below.

Table 1. Comparison table of factors influencing the force vector between aerial and water based applications of a high line.

	Aerial application Kootenay High Line System	**Moving water application Boat on a High Line**
Magnitude of Load	Constant: proportional to mass and acceleration (Force = mass x acceleration) (N)	Variable: proportional to surface area incident to flow and the square of the velocity
Direction of load (force vector)	Constant: load vector directed towards c entre of the Earth	Variable: load vector may change due to the direction of the water
Further influences	Possibly influenced by the wind, perpendicular to the load vector	1. Trim (positioning of the load) 2. size of the hull selected

It is clear that operational guidance similar to that established via an evidence base of empirical data for aerial high lines would be advantageous to practitioners rigging high lines for moving water applications. In this regard Collins and Collins (2012) state, ‘Professionals are aware that their credibility is dependent on the deep connections between practitioner and academic activity, ensuring a clear evidence base and empirical justification for their systems and structures.’ Specifically, the authors are concerned with the application to adventure sports coaching (ASC), but the connection with ASC and water rescue is well established (Ferraro, 2006: 203). The foundation work conducted by the BCCTR for aerial high lines commenced with an identification of the static load placed on the system (Mauthner and Mauthner 1996). The BCCTR went on to consider the worst case event – the highest load that a system would ever be expected to endure, so defining *static* and *dynamic* loads encountered during rope rescue operations. This proposal of the worst case event has withstood scrutiny and now underpins the rescue belay standard (ASTM, 2011) in the USA. The 10:1 SSSF was introduced so that a practical evaluation of the system integrity could be made in the field specifically; a 2kN static load may induce a dynamic force (impulse) of 12 - 15kN if the worst case event occurred, so by building to a strength of 20kN (10 x the static load) the system would not fail. Moreover, if components with a known *slip force* are introduced into a system, it follows that a catastrophic system failure is less likely to occur. Such components within high lines include the application of a prusik knot utilized to grip a host rope. An examination of the literature reveals that prusik knots made from 8mm cord are vital components within the system when applied to a more substantial parent rigging ropes, typically of 10.5 – 11mm thickness (Gorman et al., 2011:33). There is some evidence to suggest that they exhibit a reliable gripping ability of the parent rope which is utilized by the rescuer to apply tension to the parent rope via means of a mechanical advantage system (for example see Ray, 1997:67). While it is advantageous to the rescuer to employ a gripping prusik knot to apply tension, it is equally advantageous to construct the prusik in such a way that it should slip when over tensioned. This may prevent over loading of the system and is analogous to a safety valve within a hydraulic pressure system (Mauthner, personal communication, May, 2012). Anecdotally, practitioners refer to a prusik as a *slipping clutch* for the same reason. There has been some evaluations of prusik slip performance, for example see Bavarescoi (2012) who tested 6mm prusik knots applied to 11mm parent rope and PMI (2012) both authors using a slow-pull test machine. Mauthner however opinions (personal communication, May, 2012) that the slow pull test methodology used in these examples does not satisfactorily represent the activity during a rescue. Mauthner’s observations are based upon how a rescue haul team behaves, as typically a vigilant haul team will stop applying tension immediately that a prusik fails to grip the parent rope. Mauthner’s stance provides valuable guidance; in so much that the test methods utilizing machines under laboratory controlled conditions do not necessarily represent the true picture of the real world.

Anecdotally, the author has witnessed a prusik slip on a rope during a recovery from water when the line was over tensioned by an over-enthusiastic haul team, the line was glazed, and there was some evidence of the prusik melting. However the system was not tensioned to destruction. A slow pull test machine on the other hand, receives no feed-back from the prusik's gripping ability and will continue to pull until the point of destruction unless the machine operator intervenes to terminate the test procedure. For this reason Mauthner is critical of the work of many researchers, and advocates a *continuously applied tension test.* This test methodology progressively applies tension until a slip event occurs, at which a continuous tension is maintained and can be recorded. Using this methodology, Mauthner is explicit that, 'an 8mm triple-wrap prusik when applied to an 11mm rope tends to demonstrate a slip value of between 7 – 11 kN' (personal communication, May, 2012).

For this reason, it is intended during this study that a real world evaluation of a boat on a high line will incorporate the principles behind the *continuously applied tension test*. By subjecting the rig to an incrementally controlled flow of water, observations can be made of all of the components. Should a slip event occur, continuous tension will be maintained *at that tension*, unlike slow pull test methods as described elsewhere.

The development of this method will determine the load, and will be utilised to address the research question on which this thesis is based.

> "What force (N) will a boat typically encounter when placed upon a high line and deployed in moving water during swift water rescue?"

Although this thesis must stand alone, it is anticipated that by establishing the load placed upon a high line and presenting the methods for peer review, that the foundation for rescue operational guidance based upon the load may be developed.

A suggested process to that end point would include;

1. Establishment of the load, (the research question),
2. A proposed worst case event (WCE),
3. The identification of a load rating that can accommodate the worst case event. This rating will include a safety factor.

To answer this research question, the following 4 hypotheses are presented and reflect an approach to solve a multi-dimensional question. It is conjectured that the load will be determined by three independent variables, trim (the positioning of the load within the boat), the size of hull selected and the stream velocity in which the boat is positioned.

2.10 Hypotheses and Worst Case Event Description

Hypothesis 1

The force in the highline will increase exponentially as the stream velocity rises.

This hypothesis is based up the work of O'Shea which identifies the force induced by water flowing incident to an object positioned in a flow is proportional to the square of the velocity. Because force is proportional to the square of the velocity (v^2) an *exponential* increase in force is anticipated

$$\text{Force} = \text{density of fluid} \times \text{velocity}^2 \times \text{area} \qquad (1)$$

Hypothesis 2

A small hull size will result in a smaller force induced on the highline for a given stream velocity.

Similar to hypothesis 1, this is based on the force induced by water flowing incident to an object positioned in a flow is proportional to the area.

$$\text{Force} = \text{density of fluid} \times \text{velocity}^2 \times \text{area} \qquad (1)$$

Hypothesis 3

By locating the load to the rear of the craft (aft trim), the force for a given stream velocity will be less than neutral trim.

Because by placing the load to the rear of the boat, the bow will be lifted, so reducing the surface area incident to the current flow vector.

Hypothesis 4

By locating the load to the front (bow trim), the force for a given stream velocity will be greater than a neutral trim.

Because the bow will be pushed deeper into the water so presenting a larger surface area incident to the current flow vector.

Worst Case Event – a proposal

A worst case event that a boat on a highline may experience includes a scenario during which;

1. *The boat is positioned in a high flow,*
2. *The boat is trimmed with the load towards the bow such that water pours into the boat (swamping).*
3. *A D ring anchor fails at the front of the boat subjecting the remaining D rings to a "shock load."*

Number 2 (above) is presented as a likely occurrence in the event of the Rescuer reaching forward of the bow to make contact with the Victim, so trimming the boat adversely, and allowing water into the craft. The water feature created on the upstream side of obstructions is known as a *cushion wave*, or *upstream V* (Berry, 2002:284) which has a water level elevated above the baseline, and so water is more likely to enter the front of the boat under these circumstances. This occurrence has previously been predicted (but not tested) by Smith and Stephen (2009) who state,

> '...the highline in the river application could experience a large increase in load (relative to the direction of the flow of the river) such as would occur if an attached boat were to become swamped, or floating debris were to entangle the boat.'

Number 3 (above) is based upon the premise that dynamic events lead to a greater impulse force than created by the static load alone. By analogy, the BCCTR showed that the WCE would occur during rope rescue operations should the load fall during the edge transition. In this instance a 2kN *static* load was shown to generate a *dynamic* peak load of up to 15kN. The boat man's anchor (Ray, 1997: 91) used as a focal point of attachment during a boat on a highline utilises a *load distribution* concept which accommodates a change in the direction of the resultant force. The implication of such a construction is that in the event of an anchor failure, the slack rope induced by the released anchor leg must become tight before the anchor becomes operable. It is conjectured that this may lead to a higher force (shock load) as a consequence of the dynamic event.

2.11 Experimental Design

The author has previously made a case for the testing of equipment intended for swift water rescue to be made under real world conditions (Onions and Collins, 2012). While the test methods for individual components have been well established within Europe (for example see British Standard, 1998), an approach that evaluates all of the components constructed as a *system* is desirable. By examining the system holistically, variables such as force multiplication due to mechanical advantage may be incorporated into the overall evaluation.

To achieve the real world context, this thesis examines the forces exerted upon a tethered rescue boat, and the connected rigging (high line) due to current vector associated with the moving water. The speed of the current vector, and the nature of the stream flow must be representative of real operational conditions, and the rope rescue system employed to position the craft must be a common and appropriate method utilized by rescue personnel under these circumstances. Force imparted upon the rope rescue system will be recorded by a load cell (and ancillary equipment) placed in series with the focal point of the raft at the intersection with the tethering system (high line). Certainly this approach of placing load cells in series with components of rope rescue systems is not novel. Analogue strain gauges are used in series between an aerial high line and the anchors, used for educational purposes during Rigging for Rescue™ classes (Mauthner, 2002). Frank (2010: 169) also demonstrates this approach of gathering indicative force data for contextual educational purposes. In summary, the literature suggests that there is much performance related data associated with system components collected under test-house controlled conditions, and some evidence of indicative use of load cells placed in series with aerial rope rescue systems. There is however, little evidence found by the author of collecting data from rope systems used within a water rescue context using load cells incorporated within in the system. This approach underpins the methodology of this thesis, the success and validity of which will be discussed within the Discussion.

The *independent variables* to be controlled within this real-world analysis are average stream velocity (ms^{-1}), the positioning of the rescuer within the craft (trim) and the type of craft (and hence hull size) that rescue practitioners may select.

The dependent variable, force (N) is to be recorded via a load cell positioned in series with the reeve line (Figure 3, page 31).

2.12 Representative Flow

The boat on a highline must be deployed into a current vector with a range of average stream velocities encountered during real-world deployments.
The NFPA (2009) state that threshold velocity for swiftwater starts at 1 knot (0.51 ms^{-1}), and in the UK, the DEFRA Concept of operations states 10 mph (4.47 ms^{-1}) as the maximum water velocity that a rescue boat should be capable of operating in. (Department for Environment, Food and Rural Affairs, 2011). Therefore the testing procedures should include a water velocity range in increments to accommodate the range **0.5 – 4.5 ms^{-1}** to reflect accurately the full range that rescue practitioners may expect to find in the field.

3.0 METHODS

3.1 Testing Venue

The field work was conducted at the Tees Barrage International White Water Centre (TBIWWC) near Stockton on Tees in the UK during December 2011 and January 2012. The facility is a purpose built white water course utilising a Palm Rapid Block ™ system to construct features within the channel. The blocks are used to construct features in the channel bed (bed morphology) which create surface features including waves, eddies and hydraulic jumps.

The water flow around the course is maintained by a combination of water fed under gravity from the River Tees and by four Archimedean screws which may be controlled to augment the flow within the channel. The course is managed to maximise the use of gravity-fed water from the River Tees which is dependent upon the height difference (head of water) either side of the Tees Barrage due to the state of the tide. When the tide has ebbed, the operators maximise the use of gravity fed water and the Archimedean screws are switched off. Conversely when the tide has flooded, there is no height difference at the barrage, and full use of the screws is made. The site is managed to achieve usable flows within the channels by the combined use of gravity and pumped flow, bringing any number of the four screws on-line at any state of the tide.

Use of the site was negotiated, during which the Rapid Blocks™ were removed from the channel so producing an unrestricted jet of water. A suitable test location was chosen within the channel that had a gradient to achieve an elevated water velocity. The Rapid Blocks were re-arranged to produce a parallel-sided channel.

3.2 Calibration and Control of Water Velocity (v)

The TBIWWC was able to provide nominal pumped volumes ($m^3\ s^{-1}$), however the stream velocity was observed to change at different locations in the course, so a method was sought to calculate the average stream velocity at the specific location where the force determination was planned to take place. The method identified from the literature, and in frequent use by Hydrologists in the field (Gierke, 2002), is the Manning formula as described by many classical hydrological texts (for example see Akan (2006). The Manning formula is an empirical tool for determining discharge with respect to the potential energy of the flow, the nature and composition (roughness) of the channel bed.

The test channel was selected as exhibiting a constant cross sectional area resulting in steady flow. Further, the test site was selected with a fixed, constant and known gradient with consistent use of concrete during the channel construction.

3.3 Test Channel Construction

A parallel sided channel, 4.5m in width was constructed in the steepest gradient available at the TBIWWC. The channel was constructed with Palm Rapid Blocks™ to allow a potential 1.5 m depth of water in the testing location. The blocks are positioned by means of an inverted “T” section steel channel cast into the concrete bed of the main channel. Location is achieved by long threaded bars that align with the “T” section. Channel block walls are constructed so that the adjoining blocks are off-set with the joins on the preceding “course” as per good brick laying practice.

3.4 Pumped Flow Calculations

Measurements were taken from the test site to enable the relationship between pumped volume and average stream velocity to be established. A steel tape measure was used to collect the dimensions of the channel width (m) and the channel length (m). The slope of the channel was calculated by referencing the engineering drawings of the site. The levels were obtained from the top and bottom of the gradient and subtracted (height lost) and divided by the channel length.

Slope = (top datum – bottom datum) / channel length.

The facility operators were requested to introduce flow into the channel via the Archimedean screws in staged increments, so the average depth could be established at each setting. It was found by observation that the minimum pump setting of 55% capacity introduced just enough flow into the test channel to allow the raft to float. This was established as the lowest minimum flow during the test series. The Facility Operators were requested to set 55, 65, 75, 85 and 100% flows into the channel. At each stage the average depth of the water in the centre line of the channel was recorded (m). The procedure was coordinated via VHF two way radios, and a settling time of approximately 5 minutes was allowed for the flow to settle so that a constant value for depth could be established.

The table APPENDIX 1 shows the recorded values from the channel, and Manning's formula with a Manning's constant (*n*) selected of 0.015 for concrete. This procedure established a calibration curve for the unique channel (constructed with Palm Rapid Blocks™) for pump capacity (%) and *average stream velocity* (m s^{-1}).

The data collected during this procedure were utilised to calculate average stream velocity at each increment and is tabulated in Appendix 1. A graph (Appendix 1) shows the relationship between the nominal pumped volume and the derived average stream velocity. The range of stream velocities available at the site; 0.6, 1.5, 2.5, 4.2 and 5.4 ms^{-1} reflect real-world operable conditions as required by the National Flood Enhancement Project Concept of Operations (DEFRA, 2012).

This method of average stream velocity determination is presented as being preferable to taking live *snap shot* velocity readings via a hand held ultra sonic/Doppler shift device. It was conjectured that by adjusting the position of the load in the craft during the testing (trim), the hull would be exposed to a varying depth of water. Because the stream velocity changes with respect to depth, it is important to calculate the *average* stream velocity where as live Doppler shift devices record a value from a fixed location just under the surface. Further to, it was anticipated that the craft would change its position with respect to flow and trim, so an average (both in terms of surface position and depth) value would be appropriate.

3.5 Types of Craft Evaluated

Two types of contrasting craft were selected for testing purposes; a Eurocraft measuring 4.5 m in length (Figure 3), and an MFC Rescue Sled™ measuring 2.6 m in length (Figure 4). The Eurocraft offers a large stable platform for the rescue team to work in, and has capacity for carrying multiple casualties. It is however relatively large and therefore impractical to use in some areas of swiftwater. By contrast the MFC Rescue Sled™ is much smaller so may offer better access under some circumstances, but is less stable and has a reduced capacity. Both craft are representative of those in common use by water rescue teams in the UK.

Figure 3. A Eurocraft raft positioned in the testing channel. Note the construction with large tubes (sponsens) contributing to the enhanced stability of the craft and the potential for carrying multiple passengers.

Figure 4. An MFC Rescue Sled™ shown during a rescue from vehicles in water training class. The car is aligned with the direction of the current (bonnet facing up-stream) and the rescuer is using hand signals to indicate that the sled should be moved rearwards. Note the smaller tubes (sponsens) and reduced carrying capacity of the sled.

3.6 Load Positioning (Trim)

The three person load (representing the rescuer, helmsman and patient) were positioned centrally within the Eurocraft (deemed to be neutrally trimmed), positioned towards the rear (aft trim) and towards the front bow trim). To ensure consistency of trim between each time the condition was set, the crew were briefed and given the opportunity to practice on dry land exactly where to position themselves. Pre-existing features on the raft tubes (sponsens) were used as reference.

The MFC Rescue Sled, being a much smaller craft was tested with a smaller load consisting of a single helm and victim (n=2).

3.7 Personal Protective Equipment (PPE) and Safety and Management

Clearly, evaluating the forces on a tethered boat attached to a high line within context exposes the participants to a degree of risk. Consequently, the Technicians were selected on the basis of their qualification which was mapped against the Concept of Operations module 3 training syllabus (DEFRA, 2012). The Technicians were equipped with appropriate personal protective equipment (PPE) including water rescue boots, dry suit, thermal under-suit, knife, helmet and a personal floatation device (PFD).

3.8 Testing Procedure

3.8.1 Hypothesis 1

The force induced upon the highline will increase rapidly as the stream velocity rises.

The boat (Eurocraft hull) and associated rigging was set up as per Figure 1 with the addition of a Force Logic universal column load™ cell connected in series between the focal point of the anchor on the raft and the attachment point to the high-line (Figure 3). A 30m length of data cable was connected to an in-line signal amplifier positioned on the bank side which was used to collect streamed analogue data (Force/time) throughout the procedure via this equipment.

Figure 3. Force Logic Universal Load Cell and data cable positioned in between anchor leg focal point and connection to high line.

The load cell, data cable length and amplifier had been calibrated by the manufacturer as a combined unit using a 5-point calibration procedure. A Data Translation™ analogue to digital signal convertor was used to transfer the mV signal to a laptop PC and was exported to Microsoft Excel.

The crew (n=3 technicians, representing Helm, Rescuer and Victim) were positioned centrally in the boat (neutral trim) and maintained constantly. The water in the channel was switched on incrementally at 55, 65, 75, 85 and 100% flow and at each increment; the boat was deployed into the current vector via the high line.

The raft was positioned consistently mid-stream in the flow by the reeved high line as illustrated in Figure 1. Two Water Rescue Technicians controlled the tag lines (moved the craft across the flow) and the reeve line (moved the craft up or down stream). The leading edge of the bow of the craft was aligned with a marker placed on the side of the channel to ensure that the craft was positioned in the same place in the channel on each deployment. The craft was positioned mid-stream, which was determined by the helmsman using a length of timber cut specifically to be equal distant from each of the channel walls.

VHF communication was used to coordinate the requested pumped flow increment, and a five minute pause allowed for the flow rate to become constant. The raft was positioned into the flow, with the data recording equipment set to record every 0.1 seconds.

The Manufacturer’s calibration curve was used to convert the mV signal to force (N) and the data were manipulated using MS Excel™ and is detailed in the Results section.

The nominal pumped volumes described in (4) were converted into average stream velocity (ms^{-1}) via the Manning calculations and calibration curve (APPENDIX 1).
A field notebook and digital camera were used to record a chronology of the events during each deployment. The notes and images were used after the fieldwork had been completed to provide annotations of the force profiles.

3.8.2 Hypothesis 2

A small hull size will result in a smaller force induced on the highline for a given stream velocity.

The testing procedure for Hypothesis 1 was repeated for consistency. The following changes were made to the independent variables to test the hypothesis;

a. The smaller MFC Rescue Sled was adopted. It was rigged with a load distribution anchor identical to the Eurocraft hull.
b. The MFC Rescue Sled had a crew of n=2 (Helm and Victim) and therefore a smaller load than that of the Eurocraft (n=3).

The Sled was deployed into an identical set of flow increments so that a like-for-like data set was recorded (Results).

3.8.3 Hypothesis 3

By locating the load to the rear of the craft (aft trim), the force for a given stream velocity will be less than neutral trim.

The testing procedure for Hypothesis 1 was repeated for consistency with the load (n=3) positioned on the rear tube of the Eurocraft boat and maintained constantly throughout the test.

Force data were tabulated (Results) and compared with the data from Hypothesis 1, using the neutral trimmed data as reference for the data recorded during this hypothesis testing.

3.8.4 Hypothesis 4

By locating the load to the front (bow trim), the force for a given stream velocity will be greater than a neutral trim.

The testing procedure for Hypothesis 1 was repeated for with the load (n=3) positioned on the bow tube of the Eurocraft boat and maintained constantly (figure 4).

Figure 4. Boat set up for Bow Trim. Note three technicians placed towards the bow.

Force data were tabulated (Results) and compared with the data from Hypothesis 1, using the neutral trimmed data as reference for the data recorded from this hypothesis testing.

3.8.5 Force Determination of the Worst Case Event

A sacrificial cord was introduced into the self-equalising anchor in the middle of the three anchor legs (Figure 5).

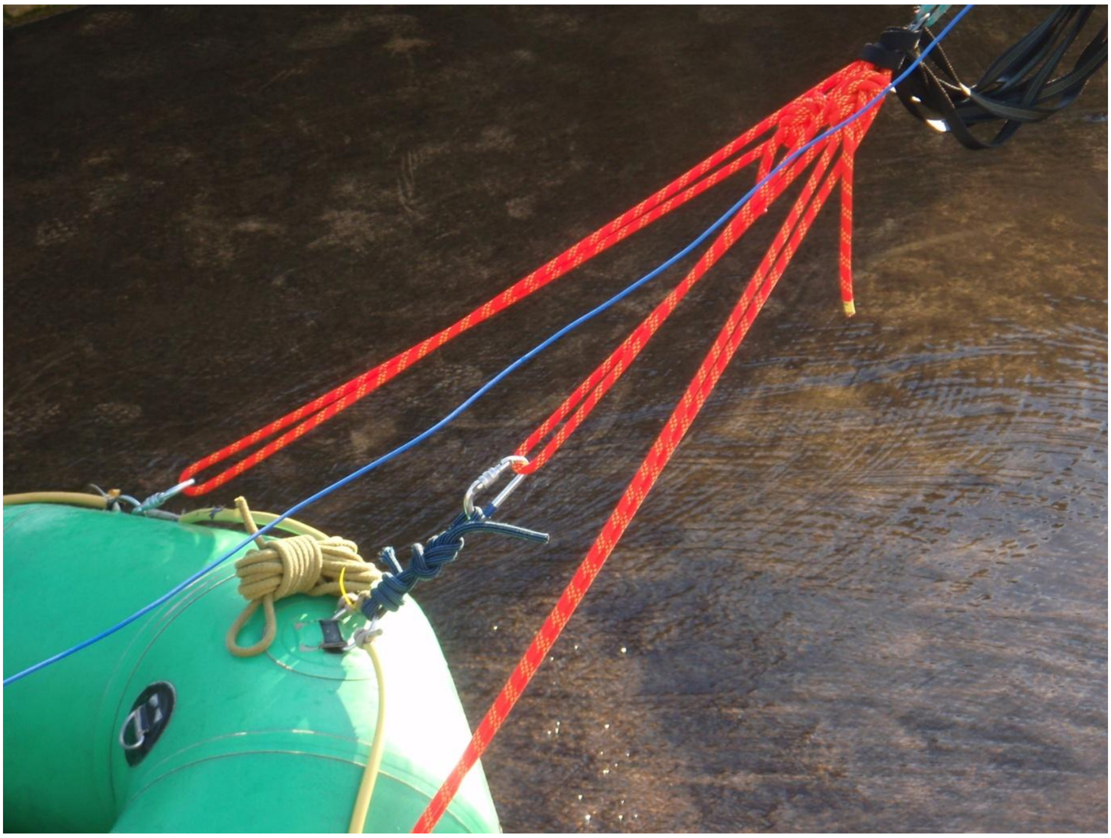


Figure 5. Sacrificial cord introduced into the middle anchor leg.

The flow was introduced into the channel at the highest flow increment and the boat was positioned mid-flow, and the crew requested to trim the boat towards the bow. When the boat had stabilised within the flow, it was deliberately swamped (filled with water) by forcing the bow down into the current vector (Figure 6). When the bow had filled with water, the sacrificial anchor leg was cut by the helmsman utilising a knife duct-taped to an extension pole.

A force against time profile was recorded throughout the procedure.

Figure 6. The bow is deliberately swamped during the testing of the Worst Case Event. The Technician is considering the implications of severing one of the anchor legs under these conditions.

3.9 Force Data Conversion (mV – N)

The data produced by the load cell were continuous mV signal (analogue) with a quoted full scale deflection of 2.000V at 10kN. The data were captured via an analogue to digital signal convertor with the associated software set to sample a value every 0.1 seconds.

A calibration certificate was obtained from the manufacturer quoting 1.987V for 10kN. It follows therefore that 0.1987mV = 1kN. This conversion factor was applied to the mV values in MS Excel™ to obtain values in N force, from which Force/Time Elapsed charts were produced.

4.0 RESULTS

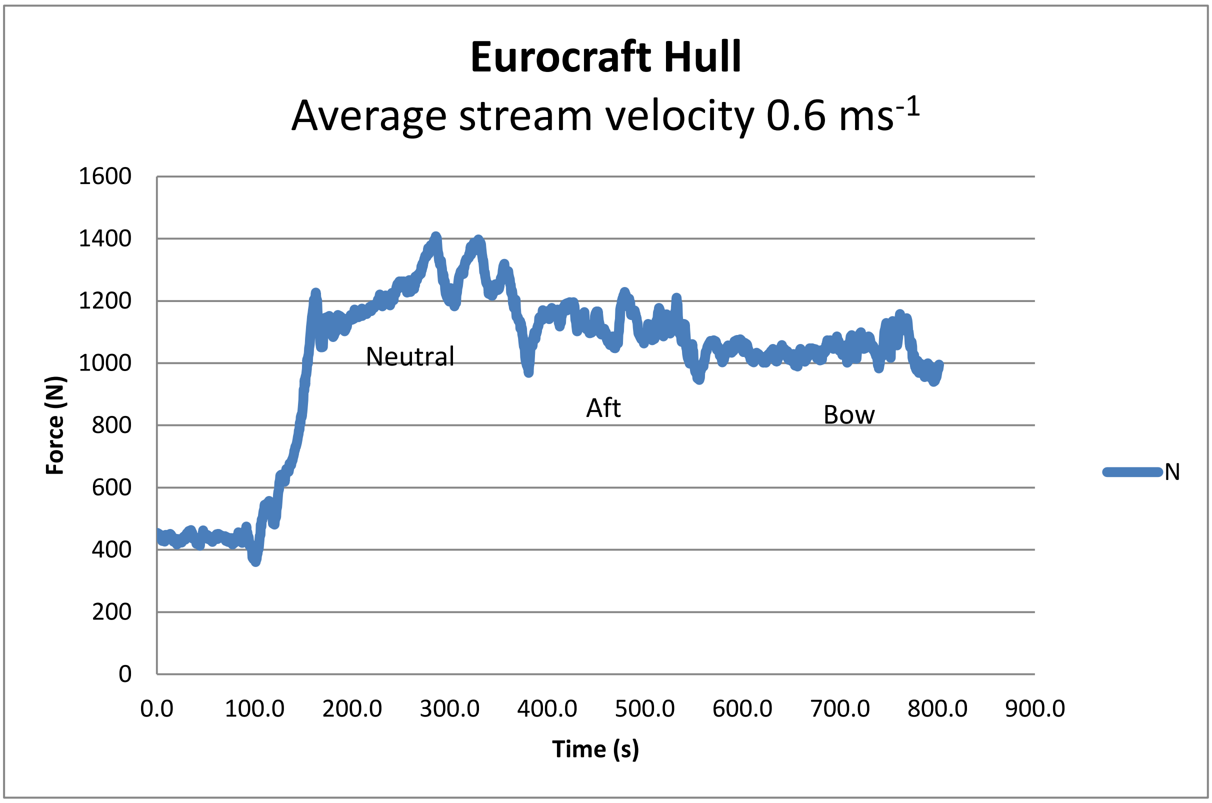
4.1 Treatment and Presentation of Data

A comma separated variable (csv) file consisting of volts (V) and time (tenths of a second) was derived from the load cell for each deployment of the boats into the flow. A new csv file was created for each of the five increments of flow (0.6, 1.5, 2.5, 4.2 and 5.4 ms^{-1}). The Voltage values were converted into force (N) by the application of the manufacturer's stated calibration factor and force (*y axis*) against time (*x axis*) were produced using Microsoft Excel™. Each condition (aft/neutral/bow trim) was identified on the force graphs by cross-referencing field journal entries of the time elapsed since the start of data recording with the time on the x axis of the graph.

The force (N) against time (s) profiles are presented (4.2 – 4.6) and summary tables (including peak force and mean force are included and aligned with the testing of the four hypotheses and the worst case event (WCE).

4.1.1 Eurocraft Hull at 0.6 ms^{-1}

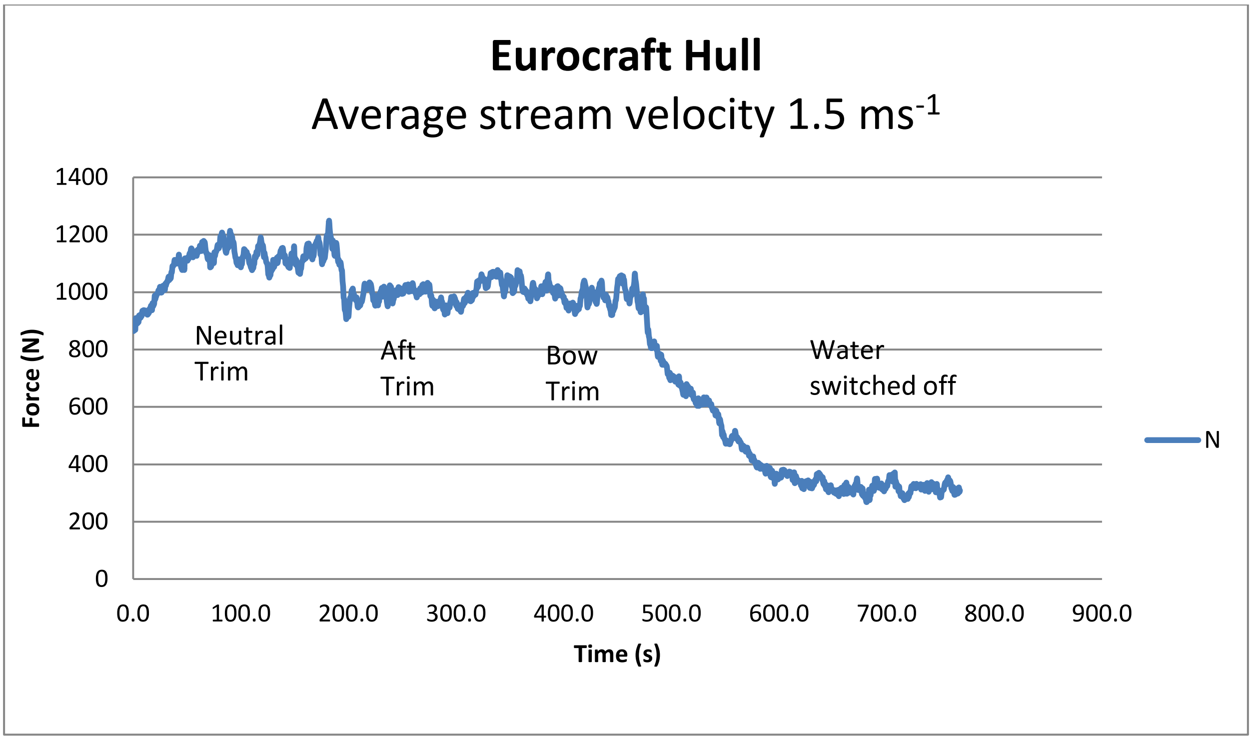
Graph 1 illustrates the three conditions relating to trim (neutral/aft/bow) for the Eurocraft boat deployed into the lowest stream velocity (0.6ms^{-1}). The value of approximately 400N for the first 100 seconds on the graph resulted from the positioning of the craft on the dry concrete channel bed with some initial pre-loading of the high line rope. Water was then introduced into the channel, after which a sharp rise in force is observed at circa 150 seconds. Thereafter the three conditions of neural, aft and bow trim have been identified, the neutral condition inducing the highest load (approximately 1.4 kN) and the bow trim condition the least load (approximately 1kN).



Graph 1 Eurocraft in 0.6 ms^{-1} average stream velocity

4.1.2 Eurocraft Hull at 1.5ms^{-1}

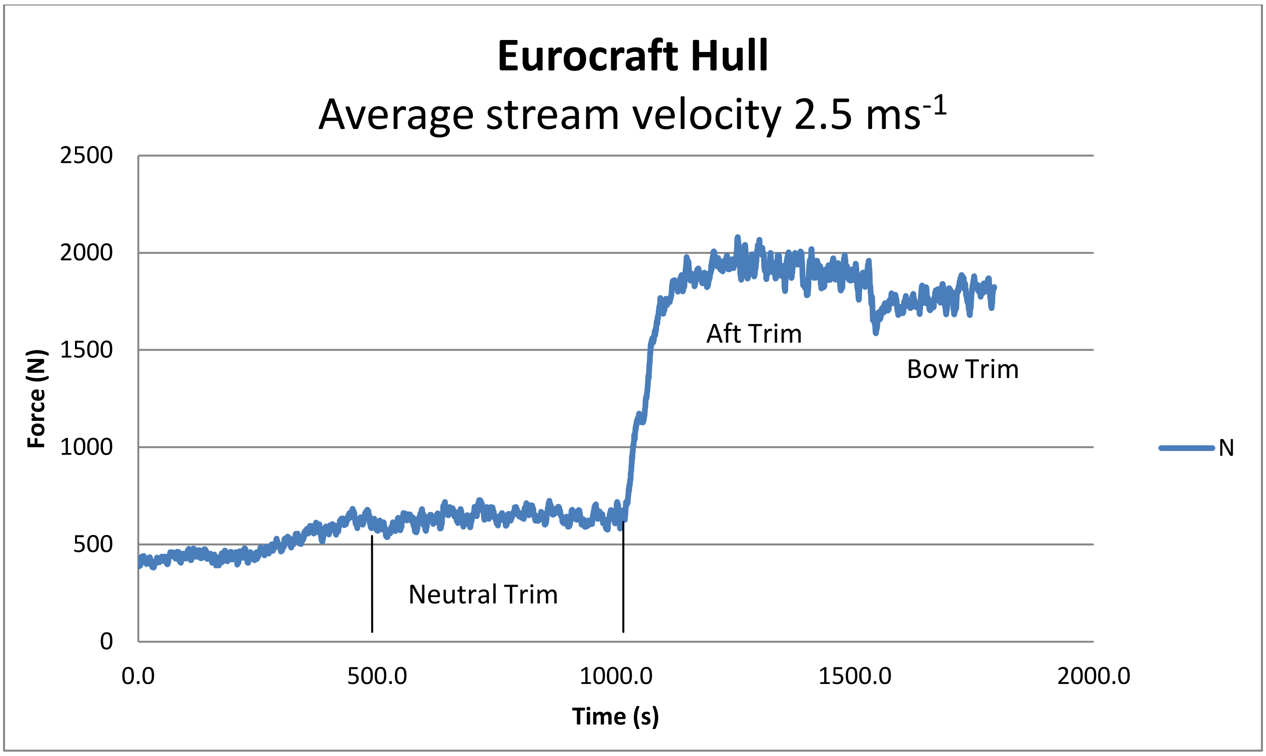
The channel flow was increased to the next increment as shown in Graph 2 which illustrates the three conditions relating to trim (neutral/aft/bow) for the Eurocraft boat deployed into a current vector of stream velocity 1.5ms^{-1}. At this velocity, the neutral trim condition has produced the highest load, and the aft trim the least load. It is of noteworthy to contrast the results in Graph 1, in which case the bow trim condition induces the lowest load. Generally however the overall force values are in the same order as those of the lower stream velocity of 0.6 ms^{-1} (Graph 1).



Graph 2 Eurocraft in 1.5 ms^{-1} average stream velocity

4.1.3 Eurocraft Hull at 2.5 ms^{-1}

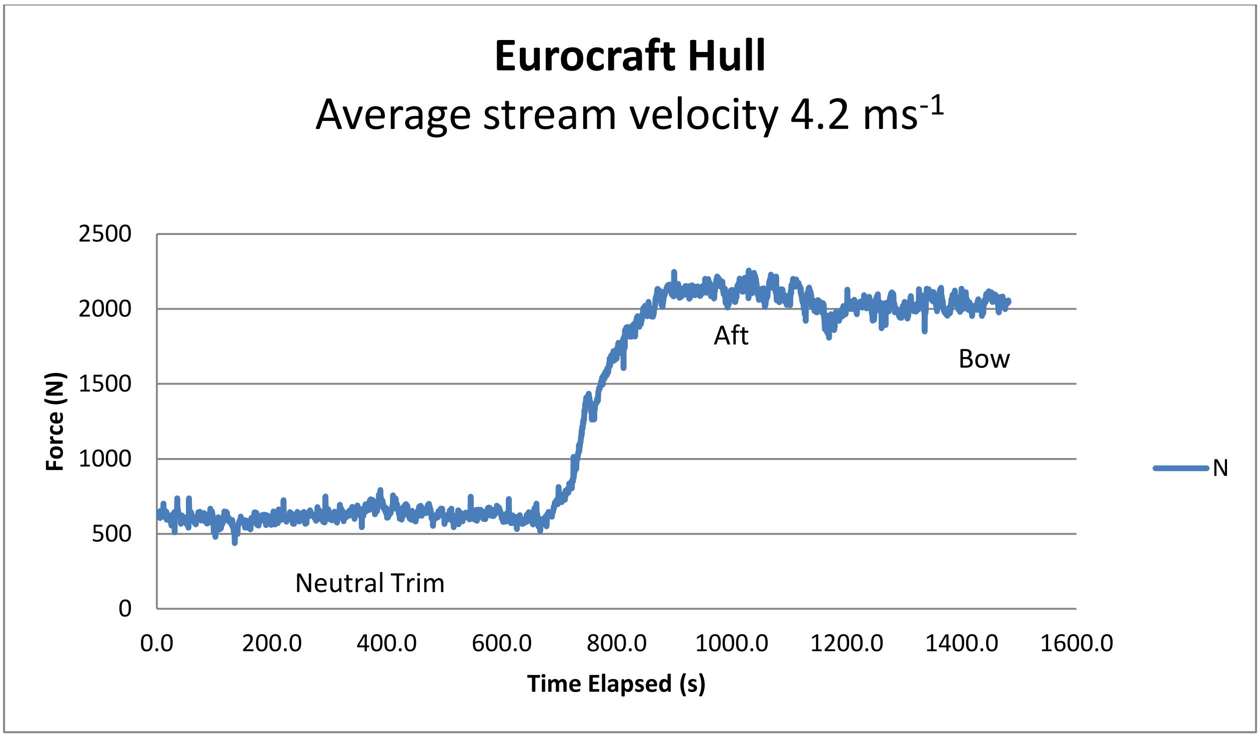
The flow was increased further to 2.5 ms^{-1}. Graph 3 illustrates the three phases relating to trim (neutral/aft/bow) for the Eurocraft boat. At this stream velocity there is a considerable rise in force if the two conditions aft and bow trim are induced when compared with the neutral trim state. The aft trim condition has induced the largest load at this stream velocity which is in the order of 2kN. Most interestingly, the neutral trim state force has *reduced* when compared to the lesser stream velocities (0.6 and 1.5 ms^{-1}) in Graphs 1 and 2 respectively.



Graph 3 Eurocraft in 2.5 ms^{-1} average stream velocity

4.1.4 Eurocraft Hull at 4.2 ms^{-1}

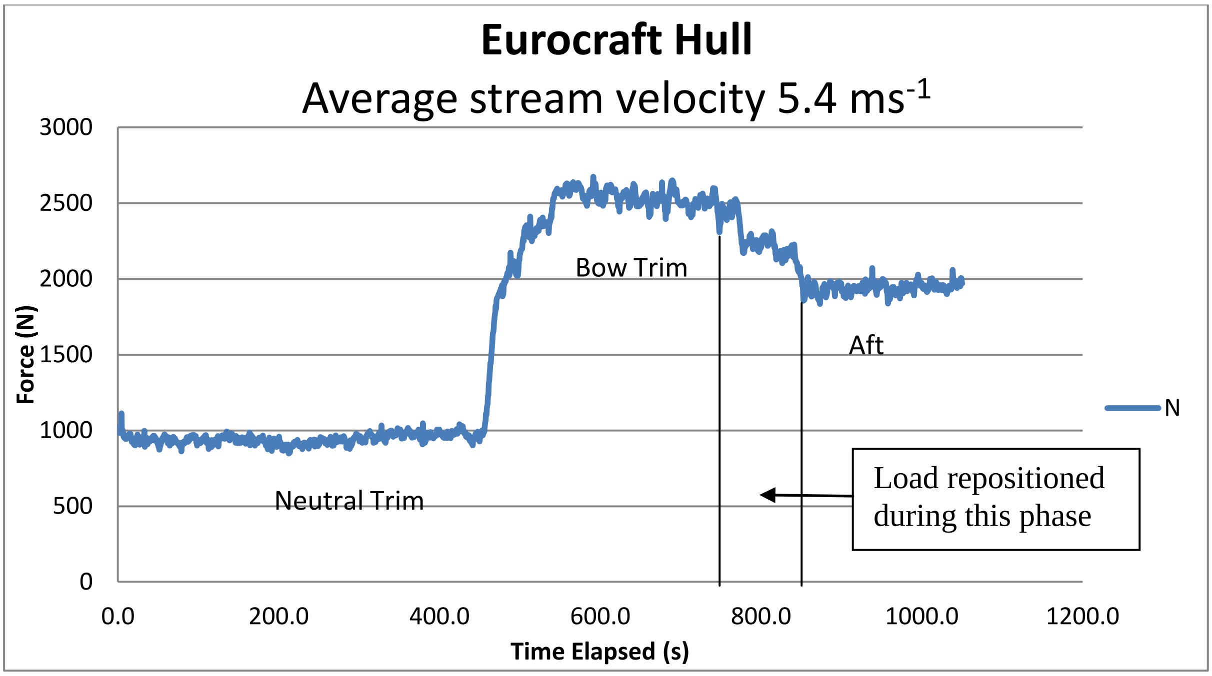
Graph 4 illustrates the three conditions of trim (neutral/aft/bow) for the Eurocraft boat in a current of average stream velocity 4.2ms^{-1}. At this stream velocity the neutral trim state induces the *least* force of the conditions investigated (approximately 0.6kN) which is a similar value to that shown in Graph 3 (2.5 ms^{-1}) for neutral trim. Indeed the overall profile of Graphs 3 and 4 are very similar, although the force value for aft and bow trim at 4.2 ms^{-1} are slightly higher (by approximately 200N) than at 2.5 ms^{-1}.



Graph 4 Eurocraft in 4.2 ms^{-1} average stream velocity

4.1.5 Eurocraft Hull at 5.4 ms^{-1}

Graph 5 illustrates the three conditions relating to trim (neutral/bow/aft) for the Eurocraft boat deployed into a current vector of average stream velocity 5.4 ms^{-1}). Please note that the order in which the Eurocraft was trimmed differs at this stream velocity, so the reader should take care when making direct comparisons between the shape of this graph with the preceding four graphs (Graphs 1 – 4). In this instance, the boat was trimmed towards the bow before the aft trim condition was induced. In this instance there is a remarkable contrast between the force induced in neutral trim state (circa 1kN) with the force when the craft is trimmed towards the bow (greater than 2.5kN). By trimming to the rear (aft) a force of approximately 2 kN is recorded which is comparable with the values shown in Graphs 3 and 4 (stream velocities of 2.5 and 4.2 ms^{-1} respectively).



Graph 5 Eurocraft in 5.4 ms^{-1} average stream velocity

4.2 Hypothesis Testing

For comparative purposes, summary tables presenting data pertaining to the conditions set during each test have been arranged. The tabulated data was derived from the raw csv files (opened in MS Excel) the functions of which were used to derive mean force, peak force and standard deviation.

4.2.1 Hypothesis 1

The force induced upon the highline will increase rapidly as the stream velocity rises.

The Eurocraft boat was used exclusively for the testing of Hypothesis 1. MS Excel was used to identify the mean force (N), peak force (N) and the standard deviation. The data for the neutral trim state at each flow increment is tabulated (Table 2).

Hypothesis 1	**Trim - Neutral**		
Average Stream Velocity (m/s)	Mean Force (N)	Peak Force (N)	Standard Deviation (N)
0.6	1220	1410	89
1.5	1130	1250	36
2.5	640	730	34
4.2	610	790	38
5.4	1130	2570	34

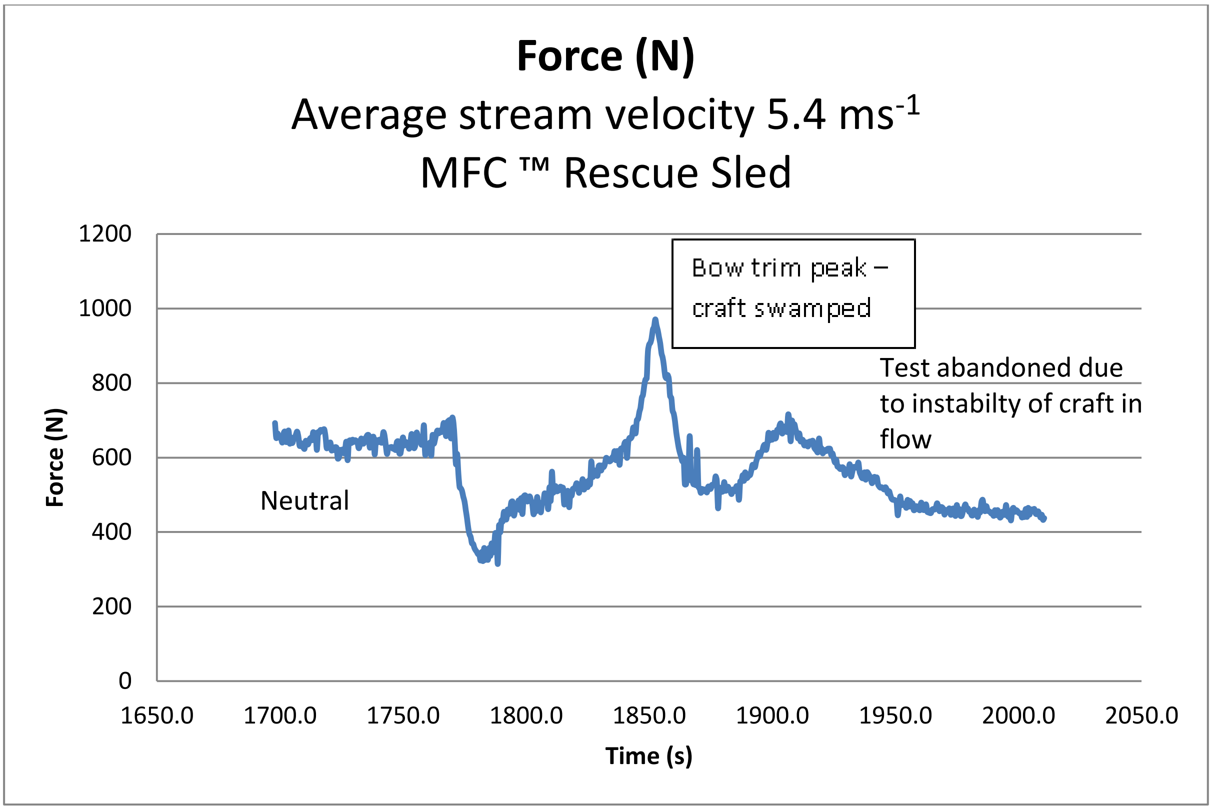
Table 2. Summary of mean and peak force induced on the highline by the Eurocraft boat, trimmed neutrally with respect to average stream velocity.

4.2.2 Hypothesis 2

A small hull size will result in a smaller force induced on the highline for a given stream velocity.

The MFC Rescue Sled Hull was used to test this hypothesis. A satisfactory trace was obtained for the MFC Rescue sled at the highest flow increment only (5.4 ms^{-1}) and is presented (Graph 6). However the craft became highly unstable in any other trim state than neural and an obvious high peak can be seen which corresponds to the Technician relocating towards the bow. For reasons of safety, the test was abandoned thereafter.

At the lower stream velocities the craft was observed to ‘surf’ in the flow without settling into the high line rope and recording a force (the equipment was not sensitive enough to record the low load value). Therefore no tabulated data is available for the stream velocities less than 5.4 ms^{-1}.



Graph 6 MFC Rescue Sled in stream velocity 5.4 ms^{-1}

4.2.3 Hypothesis 3

By location the load to the rear of the craft (aft trim), the force for a given stream velocity will be less than neutral trim.

The Eurocraft boat was used exclusively for the testing of Hypothesis 3, the data for which is tabulated below and will be compared against the neutral trim data acquired for the Eurocraft hull under the same average stream velocities. MS Excel was used to identify the mean force (N), peak force (N) and the standard deviation for the boat under aft-trim conditions.

Hypothesis 3	**Trim - Aft**		
Average Stream Velocity (m/s)	Mean Force (N)	Peak Force (N)	Standard Deviation (N)
0.6	1120	1230	52
1.5	990	1160	38
2.5	1910	2080	56
4.2	2120	2260	47
5.4	1940	2070	33

Table 3. Summary of mean and peak force induced on the highline by the Eurocraft boat, trimmed to the rear (aft) with respect to average stream velocity.

4.2.4 Hypothesis 4

By locating the load to the front (bow trim), the force for a given stream velocity will be greater than a neutral trim.

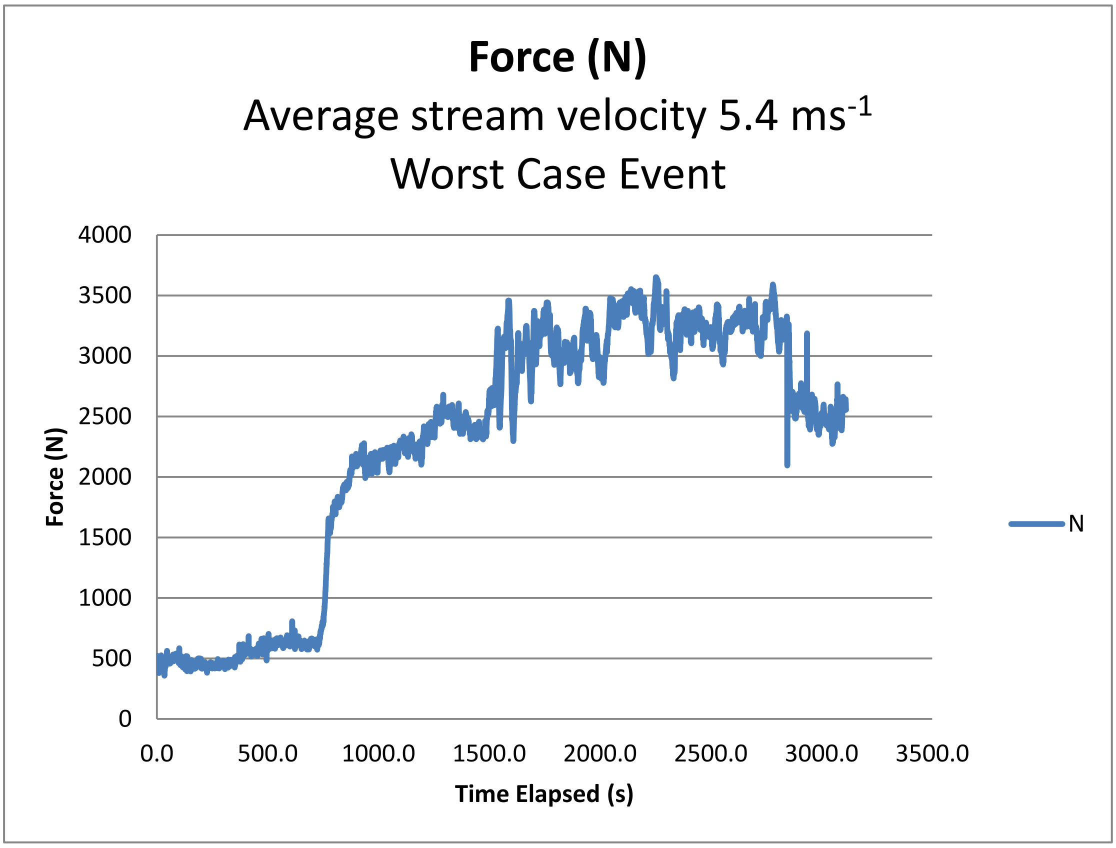
The Eurocraft boat was used exclusively for the testing of Hypothesis 4, the data for which is tabulated below and will be compared against the neutral trim data acquired for the Eurocraft hull under the same average stream velocities. MS Excel was used to identify the mean force (N), peak force (N) and the standard deviation for the boat under bow-trim conditions.

Hypothesis 4	Trim - Bow		
Average Stream Velocity (m/s)	Mean Force (N)	Peak Force (N)	Standard Deviation (N)
0.6	1050	1160	34
1.5	1000	1080	36
2.5	1770	1890	49
4.2	2030	2140	44
5.4	2530	2670	60

Table 4. Summary of mean and peak force induced on the highline by the Eurocraft boat, trimmed forward (bow trim) with respect to average stream velocity.

4.3 Worst Case Event (WCE)

The force profile (force against time) recorded is presented below (Graph 7). The Eurocraft demonstrated a high degree of instability during the intentional flooding of the boat at 5.4 ms^{-1}. The reader will notice the 'spikiness' of the data, modulating rapidly within a range of approximately 3000 – 3500N. The downward spike at 2500 seconds, which is investigated further in the Discussion section, corresponds to the simulated anchor leg failure induced by the technician. The pronounced reduction in force at 3000 seconds corresponds to the channel water pumps being switched off by request.



Graph 7. Worst case Event.

5.0 DISCUSSION

The testing regime of this thesis successfully encompassed the intended range of stream velocity of **0.6 – 5.4 m/s** set by the NFPA (2009) at the threshold of *swiftwater,* and by DEFRA (2012) as the upper limit that a swift water rescue boat team would be expected to operate within. The achieved range of testing velocities was 0.6 – 5.4 ms^{-1}. Therefore, it is proposed that the real world testing conditions are representative of those encountered by practitioners in the field.

The results are discussed with relation to the tested hypotheses. They are presented in a similar order to that of the Results section, namely Hypotheses 1,2,3,4 and Worst Case Event.

5.1 Hypothesis 1

The force induced upon the highline will increase rapidly as the stream velocity rises.

This was conjectured because the force induced by water flowing incident to an object positioned in a flow is proportional to the square of the velocity.

$$\text{Force} = \text{density of fluid} \times \text{velocity}^2 \times \text{area}$$

For the purposes of this hypothesis, the boat was maintained in neutral trim state while being subjected to an incremental increase in average stream velocity. The derived force profile (dependent variable) is presented below (Chart 1).

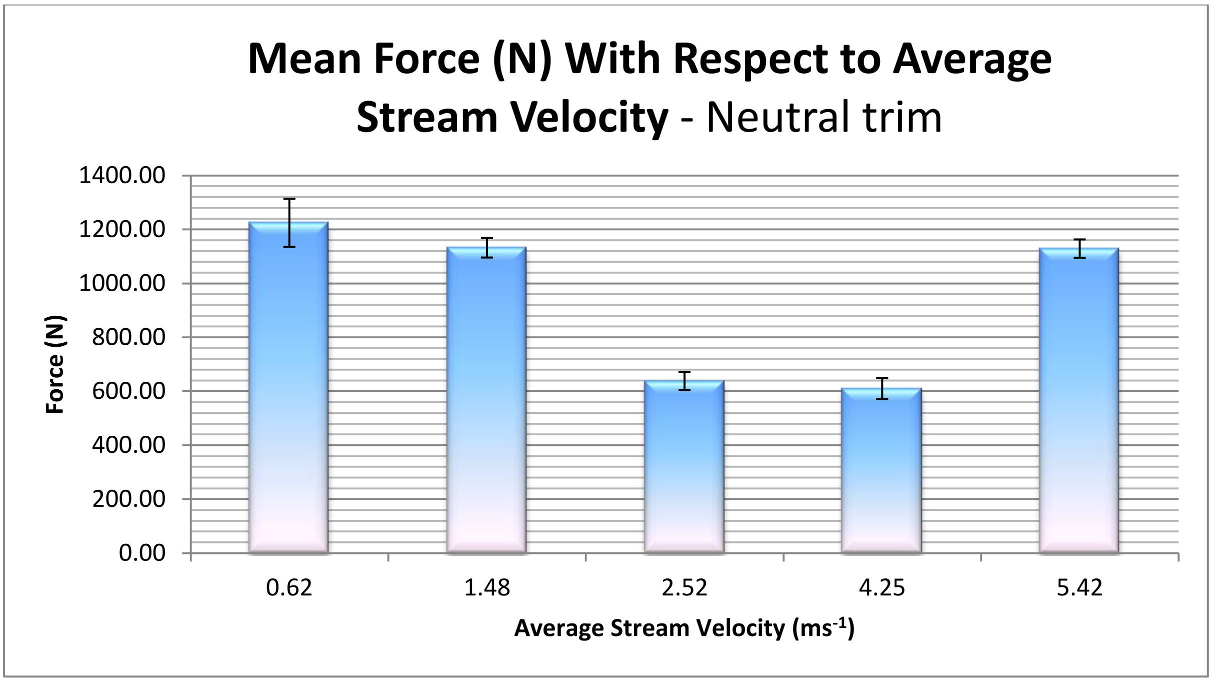


Chart 1. Mean Force (N) with respect to average stream velocity (ms^{-1}) using a Eurocraft boat. The boat was maintained with a fixed load (3 people) who were positioned centrally (neutral trim).

It can be seen that the error bars (standard deviation) are small, showing that the sampled data are close to the mean for each increment. Interestingly, the force profile reduces with respect to average stream velocity from 0.6 – 4.2 ms^{-1} and the highest force value recorded during the testing of this hypothesis (1224N) occurred at the lowest average stream velocity (0.6 ms^{-1}).

Beyond an average stream velocity of 4.2 ms^{-1} however, the force value increased up to 5.4 ms^{-1}. At the highest stream velocity, the force recorded (1130 N) was comparable with the force recorded at the lowest stream velocity (1220 N) Therefore Hypothesis 1 is *not supported* within the range of stream velocities available.

While it is counterintuitive that the force profile reduces as average stream velocity increases (up to 4.2 ms^{-1} in this study), it is possible that the boat is demonstrating a transition between *displacement* hull behaviour to *planing* hull behaviour in the range of stream velocities up to 4.2 ms^{-1}. It is conjectured that after this threshold, the hull’s ability to plane is compromised and force rises rapidly. This conjecture is based upon the theory of hull speed behaviour which has been well established within the naval and boatbuilding industry (Brewer, 1993). However, the literature revealed no application to rescue boats positioned by high lines, so this has identified a whole new line of enquiry associated with tethered rescue boats in moving water. A displacement hull has been shown to produce two waves, a bow wave and an aft wave (Fontaine and Cointe, 1997). The relative positions of these waves are determined by the square root of their wavelength, which in turn is influenced by the wetted length of the hull. A theoretical terminal velocity can be established for a given hull type and length while the boat demonstrates displacement behaviour (Miller et al, 2006). For the hull to exceed its given displacement velocity, it must transition to a planing hull behaviour, in which the hull has a reduced wetted area, and hence resistance. The literature describing this theory is concerned with engine and sail efficiency providing the relative movement through the water. In the case of the tethered boat positioned in moving water, the thrust produced by the engine, or sail is analogous to the tension (force) in the high line. Therefore this “leap of faith” which must be thoroughly investigated before powered and sailing displacement and planing hull theories can be applied to rescue boats positioned in moving water by high lines. An immediately apparent problem with this application is with the location of the anchor lines positioned at the bow of the tethered rescue boat. The position of the anchor focal point may adversely influence the behaviour of the bow as it attempts to climb over its own bow wave (Savitski and Gore, 1980) during the transition from displacement to planing hull mode. At this juncture, it is only possible to present the theory of planing and displacement hulls as a knowledgebase from which to draw during future investigation of this phenomenon.

The clear implication to rescue practitioners is that when a *lower* current velocity is encountered, the high line positioning the craft may experience a *higher* than anticipated force. This may be completely counter-intuitive so an enhanced understanding in this area can only empower an incident commander (IC) making decisions during the early phases of a water rescue.

5.2 Hypothesis 2

A small hull size will result in a smaller force induced on the highline for a given stream velocity.

This is proposed as the force induced by water flowing incident to an object positioned in a flow is proportional to the area.

$$\text{Force} = \text{density of fluid} \times \text{velocity}^2 \times \text{area}$$

For the testing of this hypothesis, a small craft (MFC Rescue Sled) was utilised and was trimmed identically to the craft used during the testing of hypothesis 1 (neutral trim) but with n=2 crew (Helm and Victim). The MFC Rescue sled presents very little resistance to the stream vector and actually failed to record a force profile at the lower increments of stream velocity, due to the sensitivity of the equipment available. A force against time profile (recorded at the highest available stream velocity) is presented below (Chart 2).

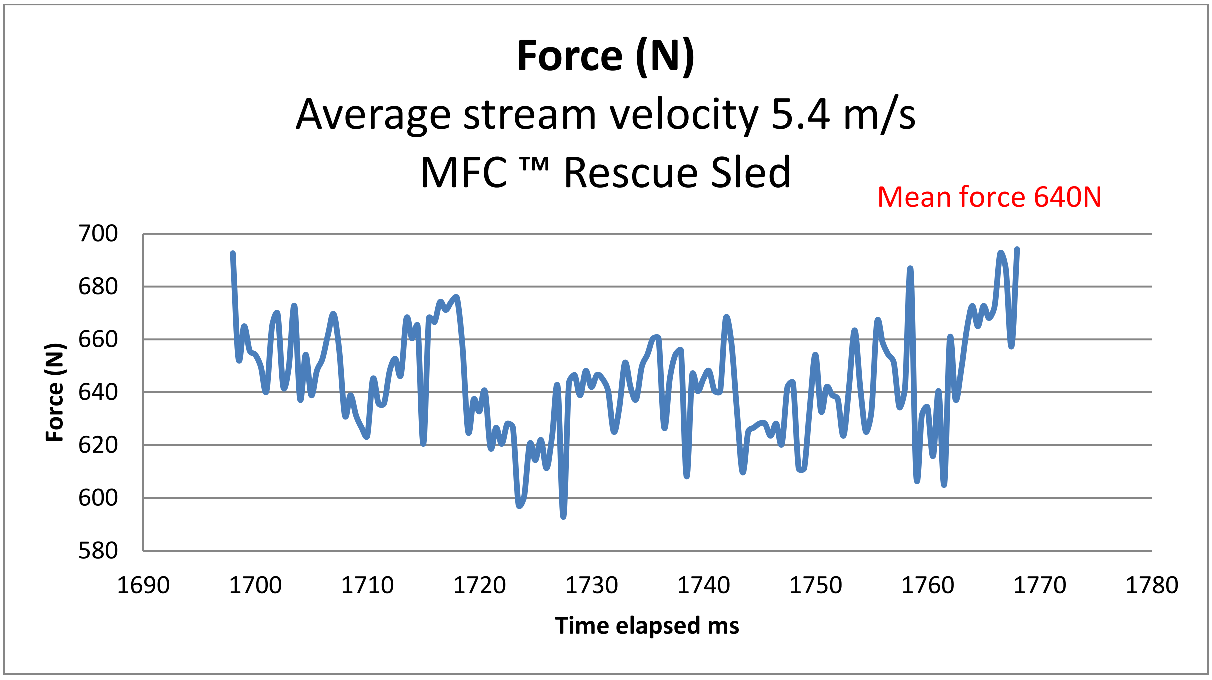


Chart 2. The MFC Rescue sled force profile at an average stream velocity of 5.4 m/s. The boat was loaded with two crew (n=2).

It would have been very useful to compare the force profile of this hull with the Eurocraft hull at each stream velocity increment on a like-for-like basis. However it is a limitation of this experiment that the small hull failed to record a force profile at the lower stream velocity increments. This is of note to the rescue practitioner, as although no empirical data is available from the lower stream velocities tested; this is due to small craft visibly not settling against the highline and inducing a load.

At the highest flow (5.4 m/s) the average force recorded for the MFC Rescue sled was 640N when compared to the average force recorded for the Eurocraft at the same average stream velocity which was 1130N. Therefore Hypothesis 2 is *supported*, but only at an average stream velocity of 5.4 m/s as no directly comparative data were recorded for the lower stream velocity increments. The smaller hull (MFC Rescue Sled) recorded a value 57% of the large hull type (Eurocraft) for a consistent trim state and average stream velocity (5.4 ms^{-1}).

At the highest increment (5.4 ms^{-1}) the sled recorded a peak force of approximately 0.7 kN. Rescue practitioners may wish to evaluate the benefits of such a small craft which exposes the high line and D-ring anchors to a reduced load. This must be off-set during the decision making process however, by the reduced stability observed during the testing of the craft when compared to a vessel with larger sponsens (Eurocraft). This instability is demonstrated by a large force spike at approximately 1760 seconds (chart 2) when the participant is asked to make a reposition (trim towards the bow). This spike and dip corresponds to when the bow of the craft is trimmed too far forward and the vessel becomes swamped with water.

5.3 Hypothesis 3

By location the load to the rear of the craft (aft trim), the force for a given stream velocity will be less than neutral trim.

This was conjectured by placing the load to the rear of the boat, the bow will be lifted, so reducing the surface area incident to the current flow vector.

A chart of the average force induced at each increment of stream velocity is presented below (Chart 3). Immediately it is apparent that the force is lowest at 1.5 ms^{-1} in this state of trim.

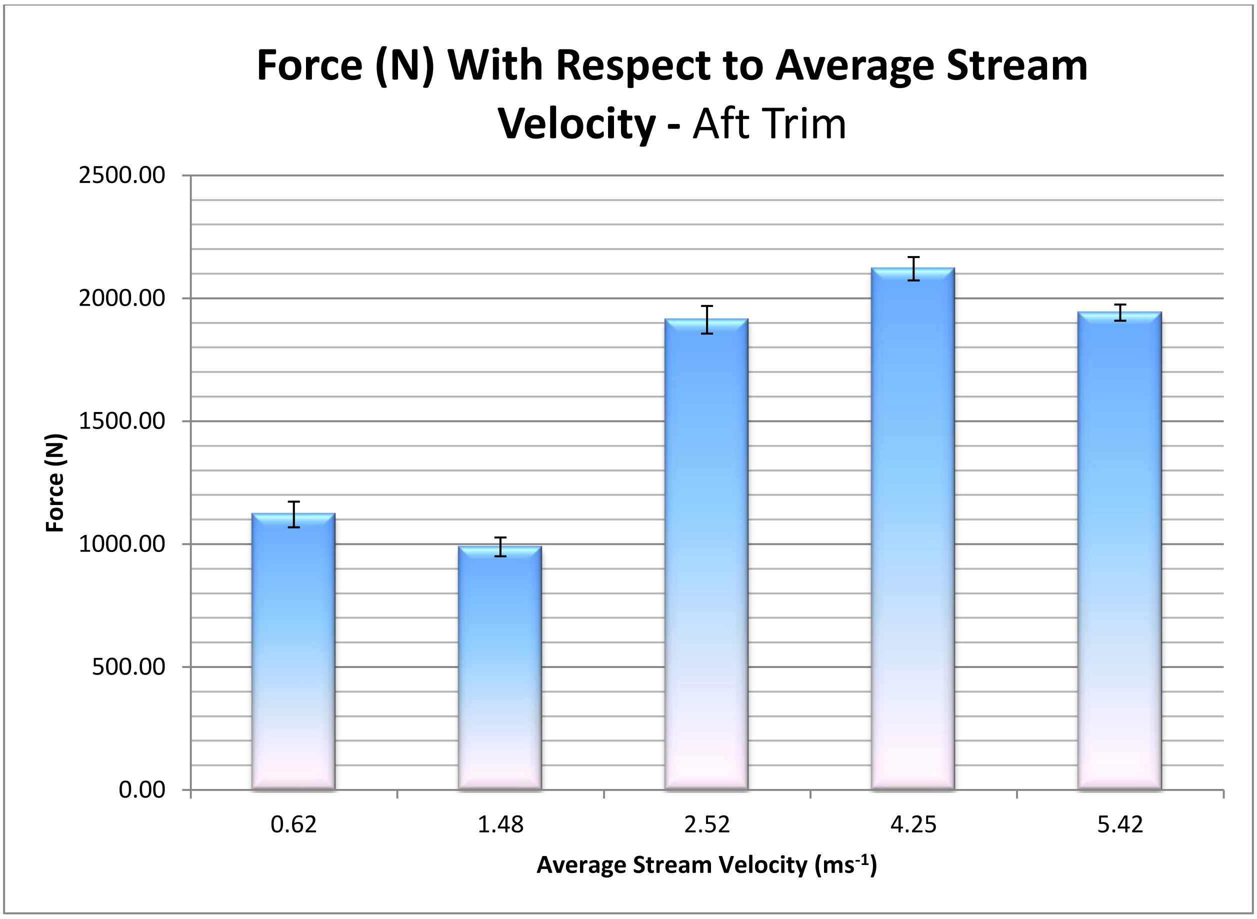


Chart 3. Force (N) with respect to average stream velocity (ms^{-1}) using a Eurocraft boat. The boat was maintained with a fixed load (3 people) who were positioned at the rear (aft trim).

For the analysis of the hypothesis, these values (aft trim) above are compared with the force values as achieved with the same craft in a neutral state of trim (Chart 4 below) set as a reference dataset.

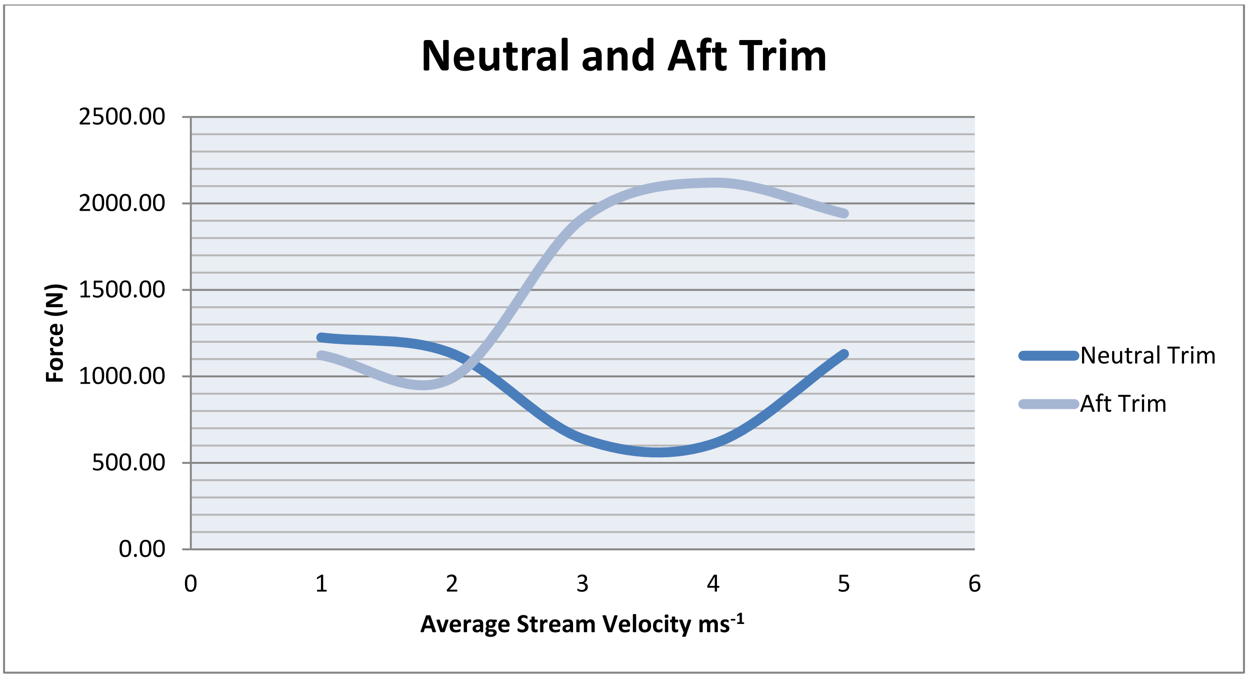


Chart 4. Line graph comparing the Eurocraft under two states of trim, Neutral and aft with respect to average stream velocity.

The force profile induced by the boat when trimmed to the rear (aft) is a mirror image of the same boat in a neutral trim state. Therefore this hypothesis is *supported* up to an average stream velocity of approximately 2ms^{-1}, but *unsupported* beyond a point where an average stream velocity of greater than 2 ms^{-1} is encountered.

There is a human factor to be concerned with in this instance as personnel may be tempted to *move away* from a fast stream vector towards the rear of the craft (aft trim) when deployed to a high stream velocity, and in doing so actually expose the high line system to an elevated force. It is reasonable to suggest that under these circumstances, by trimming to the rear, the craft was exposing more of the hull of the craft at an angle tending towards incident to the current vector, so resulting in high force value as described by O’Shea (2006).

It is of note that the two traces (aft and neutral) present as being convergent at an average stream velocity of approximately 5 ms^{-1} and above. Care should be exercised at this juncture in extrapolating the data. The traces are convergent so that the force becomes similar for both neutral and aft trim at an average stream velocity encountered beyond the testing conditions created in this test series. Further testing at an elevated stream velocity (>5 ms^{-1}) is required to progress this line of enquiry further.

5.3 Hypothesis 4

By locating the load to the front (bow trim), the force for a given stream velocity will be greater than a neutral trim.

This was presented as the bow will be pushed deeper into the water so presenting a larger surface area incident to the current flow vector. A chart of the average force induced at each increment of stream velocity is presented below (Chart 5).

Chart 5. Force (N) with respect to average stream velocity (ms^{-1}) using a Eurocraft boat. The boat was maintained with a fixed load (3 people) that was positioned at the front (bow trim).

For the testing of the hypothesis, these values above (Bow trim) are compared with the force values achieved with the same craft in a neutral state of trim (Chart 6).

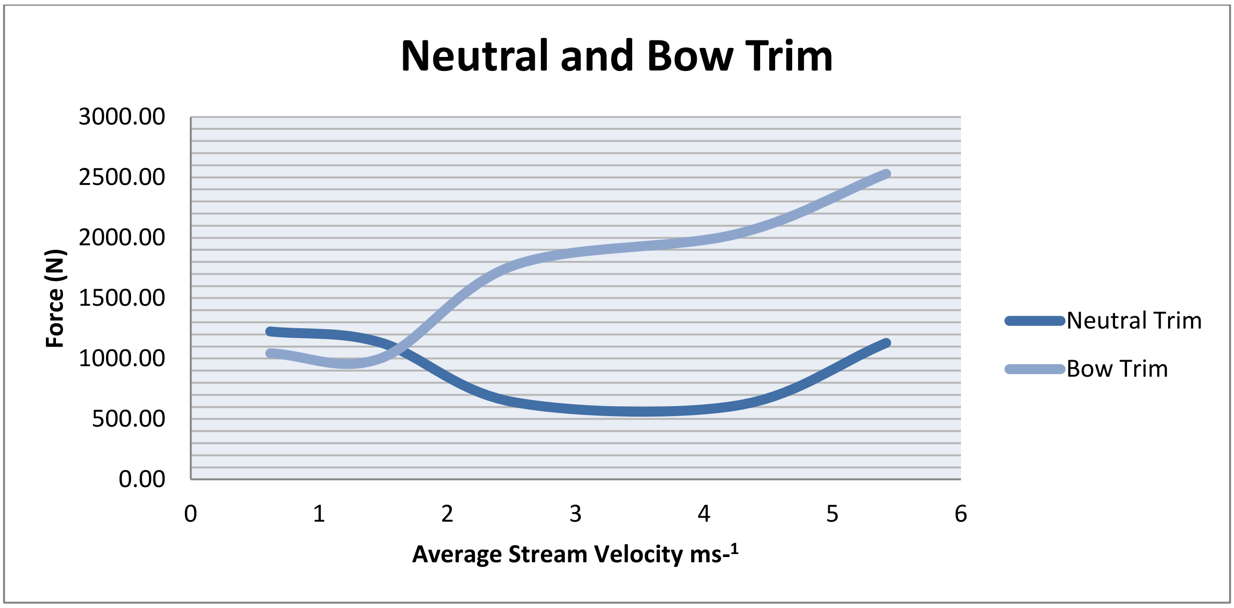


Chart 6. Line graph comparing the Eurocraft under two states of trim, Neutral and aft with respect to average stream velocity.

At a low average stream velocity (up to 1.5 ms^{-1}) the hypothesis is *unsupported* as the trace for the bow trim state is lower than the neutral trim state under these conditions. Above 1.5 ms^{-1} the hypothesis is *supported* as the trace is higher than the corresponding values for neutral trim. Above an average stream velocity of approximately 4 ms^{-1} the trace climbs with respect to force. It is conjectured that at this point (4ms^{-1}) the hull is no longer demonstrating planing behaviour and the subsequent rapid elevation in force is in line with the exponential increase associated with the velocity squared function of the formula;

Force = density of fluid x velocity^2 x area

5.5 Proposed Worst Case Event (WCE)

A worst case event that a boat on a highline may experience consists of a scenario during which The boat is positioned in a high flow, trimmed with the load towards the bow and a D ring anchor fails at the front of the boat subjecting the remaining D rings to a shock load.

This hypothesis was tested against these criteria, and the profile is presented below.

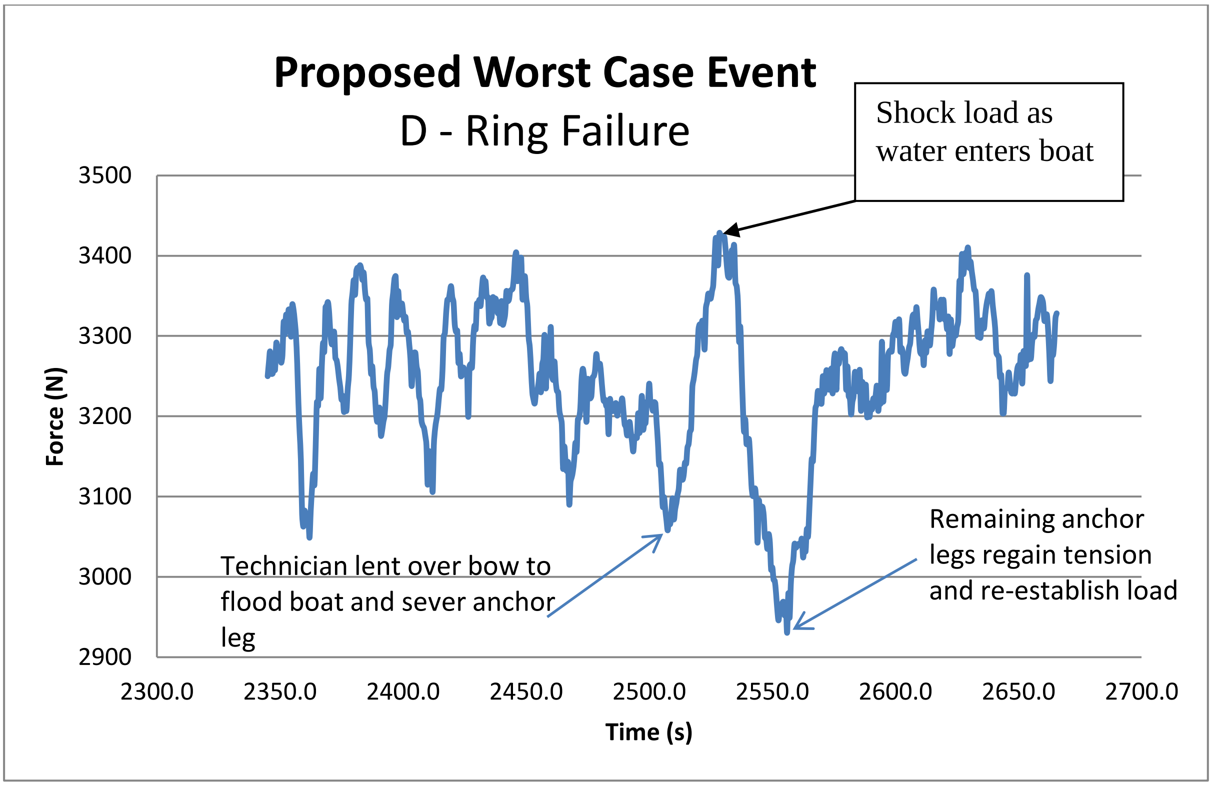


Chart 7. Force against time trace recorded during the worst case event. During this test the average stream velocity was set to 5.4 ms^{-1} and the Eurocraft boat was trimmed towards the bow (n=3 load). The annotations indicate the point at which one of the boatman's anchor legs was failed when the Technician lent forward to make the cut, and water was deliberately made to enter the boat. The peak force recorded was 3420N or approximately 3.42kN.

It was conjectured that the simulated failure of a D-Ring anchor during a period of high flow, and simultaneously adverse bow-trimming (to the point where water was entering the craft) would lead to a dynamic event and related impulse. The force profile reveals the conjecture to be inaccurate, as the peak force was achieved at the point when the bow was dipped, so allowing water into the boat. The analogy made with falling loads that create higher impulses than when suspended statically, is unrepresentative of this proposed WCE. The force profile illustrates how after the force reduction (anchor failure) the profile climbs gradually back to its original value.

5.6 Relevance of the WCE

Having established the maximum load, via a proposal and evaluation of a worst case event (WCE) to be in the order of 3.42 kN, care must be exercised if the assumption is made that this will be the largest load that the high line will experience. Trigonometric analysis of force vectors reveal that that each end station will experience a force of greater than 3.42 kN when the angle of the highline tends to an angle of greater than 120 degrees. For example if the angle of the high line tends to 160 degrees, then the force is increased at the end stations to approximately three times the load perpendicular to the tensioned high line. In this example each end station and the high line itself will be subjected to a force of approximately 10.26 kN. Conversely, by managing the high line so that the angle is smaller (for example 90 degrees, then in this instance analysis of vectors results in a high line tension of 0.7 times the load (each end station would therefore experience 0.7 x 3.42 = 2.39kN). If at 160 degrees, a force of 10.26 kN was experienced by the high line, this would exceed the gripping ability of some of the components, especially the prusik hitches which have been shown to demonstrate slipping behaviour between 7 – 11 kN. Practitioners often select canyon line, floating low stretch kernmantel (British Standard, 1998) which is strength rated in the order of 20kN. By tying hitches into the rope, testing has shown that the rating of the rope is reduced by approximately a factor of one third (see Frank, 2010:72) so the load would be approaching the ultimate tensile strength of the system under these circumstances.

Further analysis of the force profile recorded during the WCE reveals that the trace dips and spikes radically, so suggesting that the craft has become unstable within this stream velocity. The craft could be seen to be dipping and lifting as the bow filled with water on the up-stream side, so resulting in the craft bouncing against the high line resulting in short but significant impulses.

By further compounding the difficulties experienced during the worst case event, a simulated failure of a D-ring anchor was undertaken, so exposing the craft and high line to a dynamic event analogous to a load under free fall conditions in an aerial high line context. The force profile shows that under these circumstances, an impulse was not recorded. The mean force post the D-ring failure event is lower than before the event which may be explained by the craft settling into a different position within the channel beyond that of the test zone.

Of the four hypotheses proposed during this thesis, the results have shown that one has been unsupported entirely (hypothesis 1), two have been *partially* supported (Hypotheses 3 and 4) and one hypothesis has been supported (Hypothesis 2). The hypothesis that

> *A small hull size will result in a smaller force induced on the highline for a given stream velocity* (Hypothesis 2).

is supported, although it was not possible to collect data for the lower stream velocities using an MFC Rescue sled. The proposal of the worst case event (WCE) and associated criteria will require greater scrutiny (via testing) from practitioners and peer review.

5.7 Answering the research question

This thesis sets out to answer the research question;

> “What force (N) will a boat typically encounter when placed upon a high line and deployed in moving water during swift water rescue?”

Certainly the results have shown that the answer to this question is far more complex than a single empirical value. For the results of the thesis to be of value to the rescue community as a reference base and via evidence based coaching, distinction must be made between conclusions made that may be helpful in the field during the decision making process, and those conclusions that are of academic interest and suggest further lines of enquiry. To assist with the holistic consideration of this complex multi dimensional subject, a 3D surface plot is presented below. This plot illustrates the relationship between trim, average current velocity and the force induced by the Euro craft hull. The two surface plots (Chart 8a and Chart 8b) are derived from the same data, but (for clarity) show the surface plane from two different perspectives taken by the Observer.

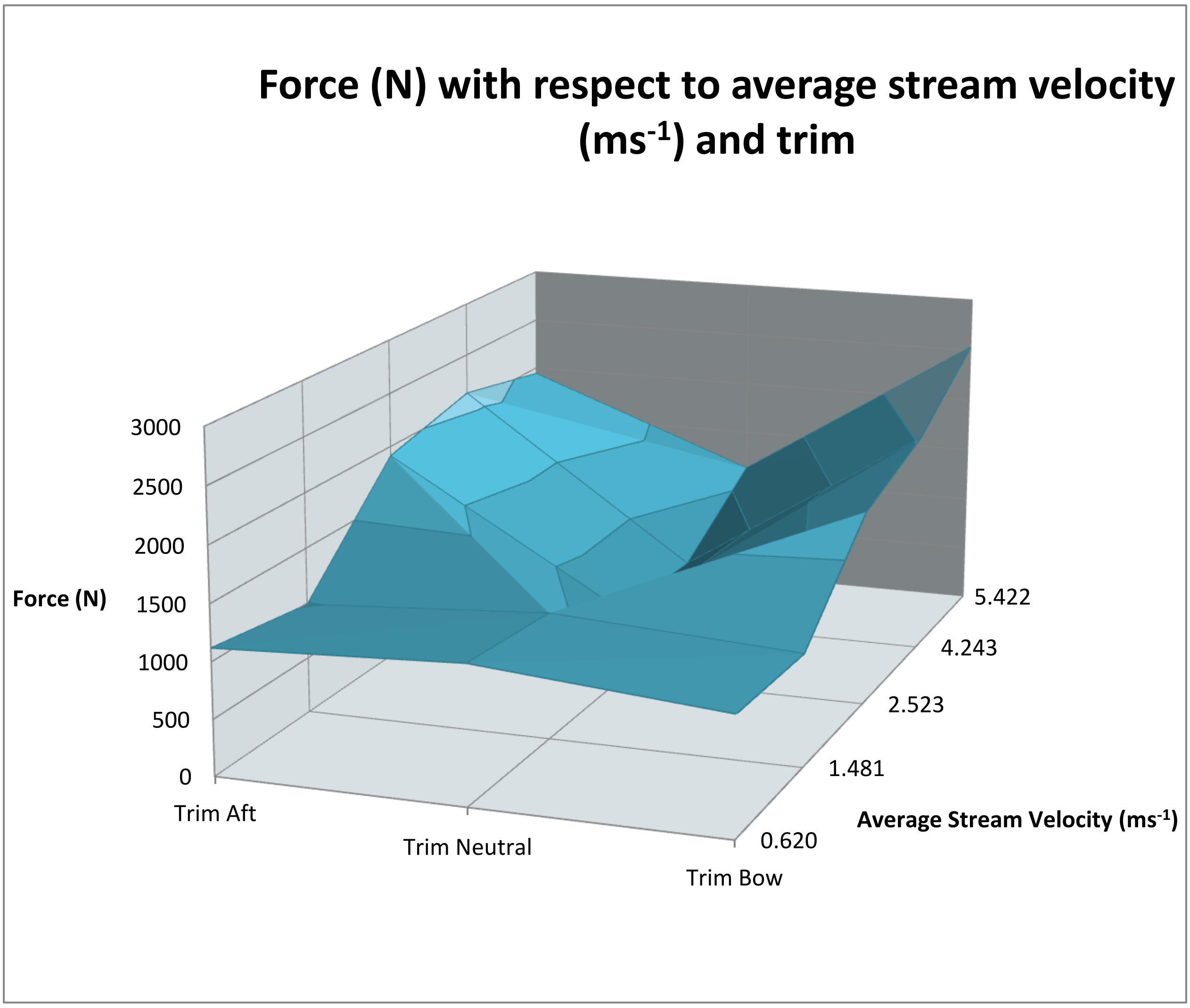


Chart 8a Surface plot demonstrating force (N) with respect to trim and average stream velocity

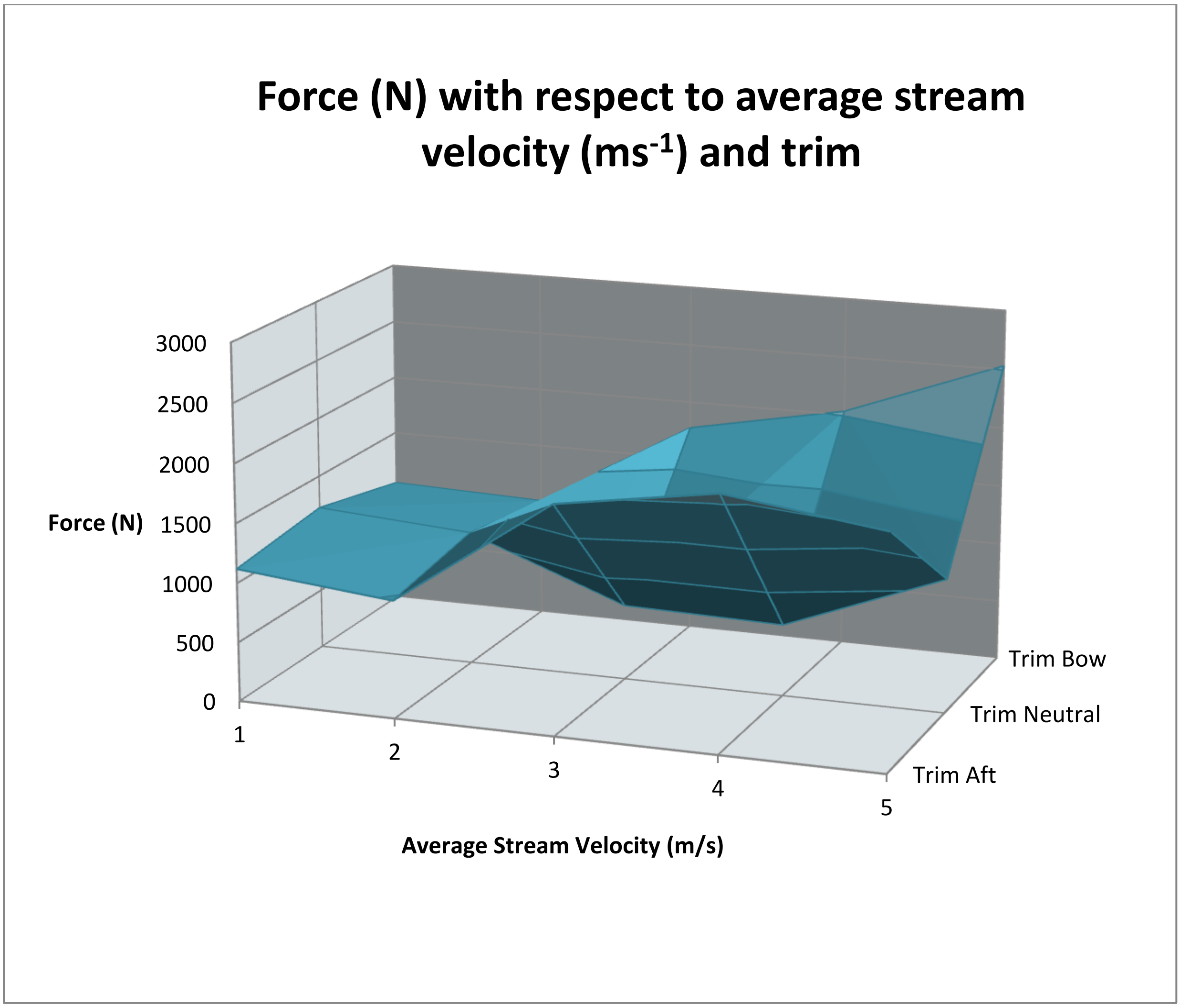


Chart 8b Surface plot demonstrating force (N) with respect to trim and average stream velocity

These images indicate that force can be managed to a consistent level by maintaining a state of neutral trim, regardless of the stream velocity to which the boat has been deployed. Under low stream velocity conditions, force values would not be unduly significant should the crew wish to relocate towards the bow or stern due to an operational requirement. Actually they are reduced at stream velocities up to 1.5 ms^{-1}. However, should the crew position themselves fore and aft while encountering stream velocities greater than 1.5 ms^{-1} significant force values should be anticipated.

5.8 Empirical Vales in Context

As the literature has not revealed many similar studies to this thesis, the data must be compared to other related fields.

The most significant work undertaken in the realm of rope rescue was by the British Columbian Council for Technical Rescue (BCCTR) who showed that the establishment of the *static* load and the *dynamic* load (generated during a worst case event) to be the foundations from which sound rope rescue systems could be engineered.

The static load for the boat on a high line study (this thesis) is taken as the highest mean value recorded for the Eurocraft when trimmed neutrally (1.20KN at 0.6 ms^{-1}). The worst case event, dynamic load is taken as 3.42kN. A comparative table of BCCTR and values from this thesis is presented below.

BCCTR Rope Rescue System and Boat on a High Line comparative Loads Force (N)		
	BCCTR	This thesis
Static load	**2.0 kN** (termed a rescue sized load – Rescuer and Victim)	**1.2kN** (Boat loaded with crew and a single victim
Peak force generated during a worst case event	**12.0 - 15.0 kN** (Rescue sized load falls 1m in space with 3m of rope in service	**3.42 kN** (boat trimmed towards the bow and water enters the boat during a deployment to a high stream velocity

Comparison table of suspended loads and loads due to boat on a high line.

Initially, it may be considered that the loads generated during this study compare favourably with those presented by the BCCTR. However as previously discussed (Relevance of the WCE) it has been shown that the dynamic force of 3.42 kN may be magnified as a function of the high line vector angles. At 160º the theoretical force multiplication of the worst case event impulse results in a force of circa 10kN, a value approaching that of the BCCTR WCE (12 – 15 kN). To reduce the manifestation of force multiplication, practitioners in the field should be mindful of managing high line angles <120º. Further development work in this area should include the formation of empirical operation rules suitable for managing boat on a high line operation. Such development work is eluded to by Smith and Stephen (2009) who state that ‘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.’

6.0 CONCLUSIONS

This thesis is concerned with the research question;

“What force (N) will a boat typically encounter when placed upon a high line and deployed in moving water during swift water rescue?”

The answer to this question is more complex than a singular figure and is conditional on the state of trim, stream velocity and the type of hull selected. Indeed for some conditions the relationship may be quite complex as the experiment suggests that for the *least* variation in resultant force, with respect to stream velocity, the boat should be maintained in a neutral trim state. Even so, when trimmed neutrally, the Eurocraft induced the largest force on the high line at the lowest incremental flow in the testing programme (1220N or approximately 1.2 kN). It is postulated that the reduction in force with respect to stream velocity could be explained by the hull demonstrating planing behaviour but this must be considered as a line of enquiry to take in subsequent research, rather than a definitive explanation of the phenomenon.

Should the craft be set up with an alternative trim arrangement, aft or bow, the Eurocraft demonstrated an elevated force when compared to a neutrally trimmed boat but only when stream velocity is greater than 2.5ms^{-1}. Conversely at a velocity less than 2.5ms^{-1} altering the trim from a neutral state produced a reduction in force.

The MFC Rescue Sled (small hull), induced a relatively small load on the highline when compared with the Eurocraft at a similar stream velocity of 5.4 ms^{-1}. A mean force of 644N was recorded for the Rescue sled which is 57% of the force produced by the Eurocraft at the same stream velocity with both craft neutrally trimmed. This low force characteristic may be a very attractive to decision makers attending water incidents who are concerned with reducing the load placed on systems. However, the instability demonstrated by the Rescue Sled in such a stream velocity (5.4 ms^{-1}) should preclude its deployment within this particular context.

The proposed WCE generated a load of approximately 3.4kN as the Eurocraft suddenly filled with water. The bow becoming ‘swamped’ by the water entering the boat under circumstances of bow trim was identified as the cause of the escalation in force. Another contributory factor which was proposed was that of a D ring anchor failure, but this did not result in a shock load. Therefore practitioners should be very mindful of un-intentional swamping of the boat as this is potentially the most significant contributor to the WCE.

This experiment has suggested that the routine load to be expected by maintaining a neutral trim state is in the order of 1.2kN and the greatest load expected (WCE) to be 3.4KN. A boat on a high line built to strength of 10 x the static load (as is often the practice within rope rescue) so incorporating a 10:1 safety factor would result in a system rated at approximately 12kN (10 x 1.2kN).

A system rated for 10x the static load would accommodate the WCE with a margin for safety). Taking the WCE as 3.4 KN, the proposed build rating of 12kN accommodates the WCE by a factor of approximately 3. However, force multiplication due to a high line constructed with a mid-point angle greater than 120º may exceed this safety factor, so practitioners should be mindful to manage the track line angle (and hence tension) all times.

7.0 RECOMMENDATIONS

1. The methods and hypotheses presented in this thesis require review to substantiate the empirical values.
2. The contributory factors leading to the WCE require scrutiny by practitioners operating in this field.
3. A longer term study, building on the findings of this thesis including a greater number of replicate determinations would enhance the statistical reliability of the data.
4. A more comprehensive investigation of the application of planning hull behaviours to describe boat behaviour is required.
5. Further evaluation of the contrasting effects of trim on the displacement hull should be undertaken.

8.0 LIMITATIONS OF STUDY

It was not possible to record reliable traces of force against time for the MFC Rescue Sled™ at stream velocity values of less than 5.42 ms^{-1}. Observation of the behaviour of the sled during low stream velocities showed that the sled appeared to *surf* without providing any tension on the high line (and load call). Therefore no force/time traces were captured for the sled at stream velocities <5.42 ms^{-1}.

To address this limitation, a smaller more sensitive load cell with an operational range of 0 – 1kN may record force values at lower stream velocities. This however is not identified as a priority as the benefits of this knowledge to the rescue community are negligible.

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Appendix 1

Calibration of the test site for average stream velocity.

Average stream velocity was calculated from the Manning Formula;

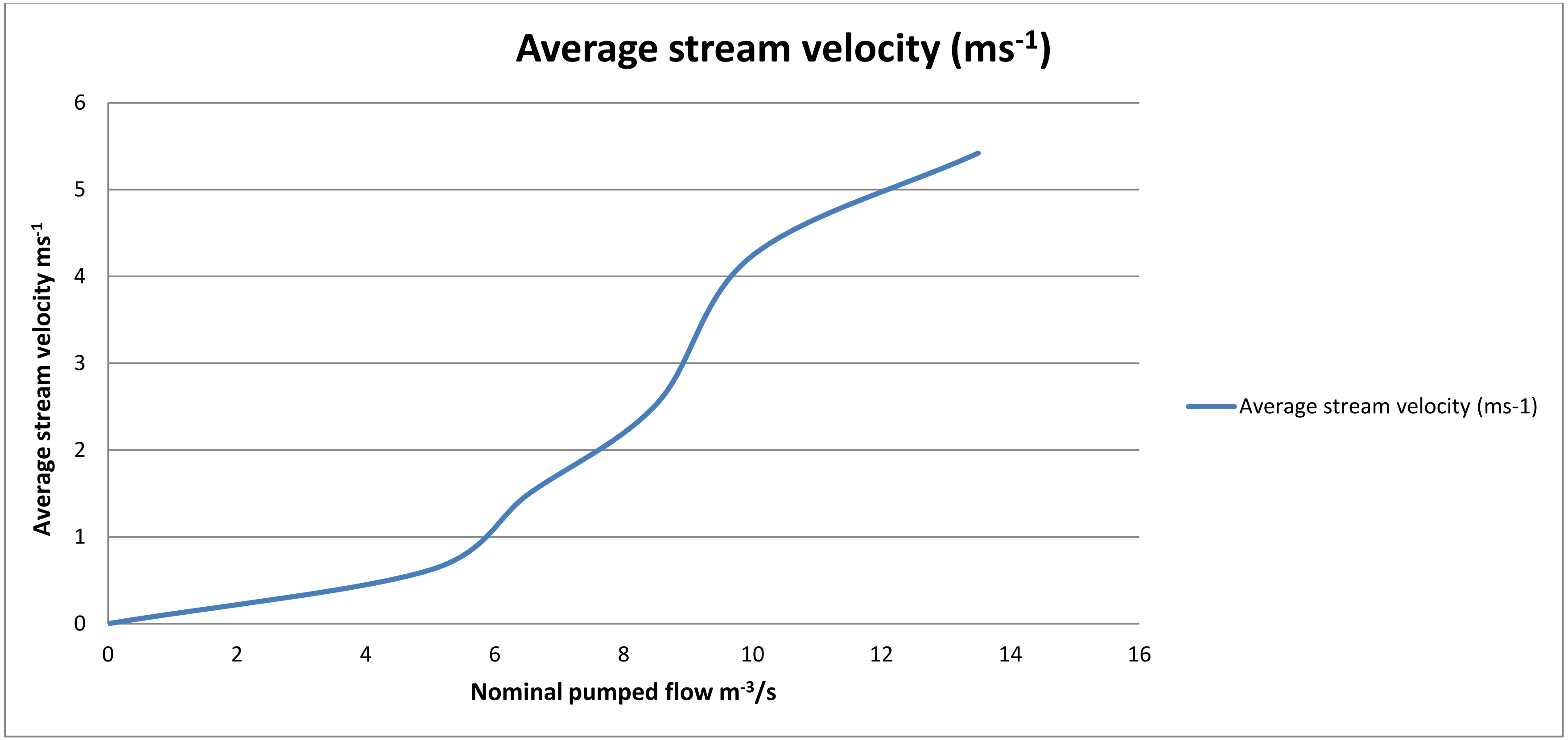
Screw Capacity (%)	**Nominal pumped Flow (m3/s)**	**Channel Width (b)**	**Hydraulic Mean Depth *y* (m)**	**Hydraulic radius (R)**	**Top datum (m)**	**Lower Datum (m)**	**Length (m)**	**Slope**	**Manning number (*n*)**	**Average stream velocity (m/s)**
0	0	4.50	0.00	0.000	0.82	0.21	9.00	0.80	0.015	0.000
55	5.0	4.50	0.30	0.265	0.82	0.21	9.00	0.80	0.015	0.620
65	6.5	4.50	0.50	0.409	0.82	0.21	9.00	0.80	0.015	1.481
75	8.5	4.50	0.70	0.534	0.82	0.21	9.00	0.80	0.015	2.523
85	10.0	4.50	1.00	0.692	0.82	0.21	9.00	0.80	0.015	4.243
100	13.5	4.50	1.20	0.783	0.82	0.21	9.00	0.80	0.015	5.422

$$V = \frac{R^{2/3} . S^{1/2}}{n}$$

Where;

V = Average stream velocity
R = Hydraulic radius
S = slope
N = Manning number

The data collected in the table above was used to produce the calibration curve below.



Flow calibration curve deriving empirical average stream velocity values for nominal pumped flows.

Appendix 2

The following practitioners have been cited as ‘personal communication’. A short bio of each commentator has been included to illustrate the importance and relevance of their opinions.

Martin Bills

Martin serves with Nottinghamshire Fire and Rescue Service, taking the lead with water rescue within his Brigade. Martin was seconded from the Fire and Rescue Service to DEFRA, joining the National Flood Enhancement Project Team. Martin’s expertise contributed greatly towards the Flood Rescue Concept of Operations – the UK model for interagency attendance to flooding incidents.

Steve Glassey

Steve is the Editor in Chief of the Journal of Search and Rescue (JSAR) and an associate lecturer in Technical Rescue Instruction with the School of Sport, Tourism and the Outdoors, University of Central Lancashire. In New Zealand Steve is the Deputy Director of the Centre for Risk Resilience and Renewal at the University of Canterbury.

Alistair Read

At a strategic level, Alistair is the National Training Officer and Subject Matter Advisor - Flooding for Mountain Rescue England and Wales (MREW). At a tactical level, Alistair is team leader with the Ogwen Valley Mountain Rescue Organisation (OVMRO) which has a considerable rope and water rescue capability.

Tim Rogers

Battalion Chief Tim Rogers has served with the Charlotte Fire Department, North Carolina for 30 years. Tim founded and co-ordinates the NC Emergency Management Aquatic Helicopter Rescue Programme (NC – HART) and the swiftwater rescue boat operations programme. He has used his extensive experience from deployments to hurricanes Frances, Ivan, Isabel and Katrina to assist the UK Chief Fire Officer’s Association (CFOA) to enhance UK resilience during flooding incidents.

Paul O’Sullivan

Paul O’Sullivan is the Managing Director of Rescue 3 (UK) Ltd. a rescue training provider delivering classes both in the UK and internationally. Paul is a recipient of the Higgins and Langley Memorial award for his significant contribution to developing the UK Fire and Rescue Service capability at water related incidents.

Richard Taylor ‘Rich T’

Master Air Crewman Richard Taylor has served with Search and Rescue Force (SARF), ‘C’ Flight 22, Squadron, RAF Valley. He is the recipient of the Queens Gallantry Medal (QGM) in 1999 and Queen’s Commendation for Gallantry in the Air (QCGA) in 2012, on both occasions for rescuing survivors from boats during high sea states. Currently Rich is serving with ‘Operational Standards’.

Squadron Leader ‘Spike’ Wright

From 2008 until 2011 Squadron Leader Spike Wright served with the Search and Rescue Force (SARF) 22 Squadron ‘C’ Flight based at RAF Valley as the Officer in Commanding. Spike was consulted during this study for his UK perspective of helicopter rescue operations, specifically the capability of a winch - equipped Sea king airframe and the suitability for tasking to water related incidents.